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Journal of the
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A WATER-BORNE RUNWAY

David Williams[1]
(Proc. Paper 1658)

Part I — General Description

Introduction and Summary

When the weight of an aeroplane approaches the 100-ton mark, the structural problems associated with landing and take-off become acute. The design of an undercarriage combining the required strength with lightness and ease of stowage faces the aeronautical engineer, while the civil engineer faces the problem of building a runway capable of standing up to the heavy landing loads without deterioration. The spreading of the load would clearly benefit the runway designer but the aircraft designer is loth to provide more than two undercarriages although he is willing to spread the load at each among a group of small high pressure wheels, since that helps stowage and also reduces weight. The result is that at any one instant practically the whole weight of the aircraft is concentrated on two small areas. A 100-ton aeroplane, for example, carrying four twin wheels at each main undercarriage puts the runway under a set of four 12-1/2-ton concentrated loads at each wheel group, and on most existing runways it would quietly push its wheels right through the surface concrete, and deep into the subsoil. The runway fails, not because the surface concrete cannot stand the local crushing action of the 150-lb. tyre pressures, but because that surface cannot perform the bridge-like function of spreading the load over the surrounding subsoil without breaking up under the bending stresses. Concrete is well known to be very weak in tension, which is why the tension side of a concrete beam is nearly always reinforced with steel. The steel rods take practically the whole of the tension, and therefore a reinforced concrete beam is very wasteful of both concrete and steel.

Nevertheless nearly all present-day runways are made with ordinary reinforced concrete and are fairly satisfactory for moderate-sized aeroplanes. It may be argued therefore that, in order to accommodate larger and heavier aeroplanes, all that needs to be done is to use concrete of correspondingly greater thickness. This is a costly business for two reasons. The first is

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that increasing the thickness of concrete increases the amount that is wasted, since the same proportion of the total is virtually inoperative as in the thinner version. The second reason is that the scaling up factor applies not only to the thickness of the concrete but also to the depth of the supporting sub-grade under the concrete. If the concrete alone is thickened up, the result is that the local support it receives from the sub-grade round the point of load application is inadequate, and the concrete is forced to seek support on a wider base more remote from the load. In the process it suffers a disproportionate amount of bending action and so is liable to failure. It is, in other words, too stiff in comparison with the sub-grade; a little more flexibility would enable it to derive a greater measure of support where it is most wanted—in the immediate neighborhood of the load. This would mean heavier, but not necessarily undue, pressure on the subgrade, which would merely be forced to provide its proper share of resistance to the load.

It can thus be appreciated that much of the costly work of pushing the foundations deeper into the soil, in order to cope with heavier loads, is forced on the runway constructor not by the need for increased strength so much as for increased stiffness. The thickened concrete must at all costs be given adequate support against bending (and cracking) under the load.

Continuing to increase the thickness of the surface layer of concrete as a means of coping with ever-increasing runway loads, as may be gathered from the above remarks, is a wrong method of approach. A much better solution is to increase the flexibility of the concrete layer rather than its thickness. This is the solution adopted by the French civil engineer M. Freyssinet, on the basis of which the experimental stretches of runway at Orly, Paris and at London Airport, Heath Row were put down. The necessary flexibility he obtains by using prestressed, instead of ordinary reinforced concrete; the term prestressing meaning that the concrete slabs are permanently compressed along their length and breadth by heavily pre-tensioned steel wires. These wires are either embedded in the concrete, which 'freezes' round them while they are fully stretched, or—the more usual technique—the slabs are cast with narrow tunnels through which the wires are later threaded and tensioned up by hydraulic jacks to be firmly anchored finally at the two ends.

The concrete in a prestressed concrete slab, so long as the slab is not overloaded, is never subjected to a tensile stress when the slab is loaded in bending. What would normally be the tension surface of the bent slab is, by virtue of the overall compression induced by the contracting tendency of the tensioned cables, still in compression and therefore free from any tendency to crack. Indeed, even if the bending load is carried to a point where the concrete is forced to accept tensile stresses at the surface, and in consequence cracks, so soon as the load is removed the cracks close under the action of the heavy tension in the cables and no harm is done. The slab is in fact ready to repeat the process indefinitely. Without prestressing, any cracks formed as the results of an overload remain open and are a permanent source of weakness in that they tend to increase and spread under successive frosts and thaws.

The great advantage of prestressed concrete, however, is that, for bending stresses up to the value of the prestress (which may be 1000 or even 2000 lb/in^2), it behaves as a perfectly flexible and elastic material. Within the limit of the prestress therefore, every element in a concrete beam, whether on the compression or the 'tension' side, is fully effective in resisting bending loads. The function of the high-tensile-steel wires is very different from that

of the steel in ordinary reinforced concrete. In the latter the concrete on the tension side of the beam does practically nothing and the steel resists the bending tensile loads directly, the stress in it varying with the external load. In the prestressed beam, on the contrary, the concrete resists the tensile bending stresses directly (by having its compression prestress reduced), the stress in the highly tensioned wires meanwhile remaining nearly constant.

A hardly less important advantage of the prestressing technique is the great saving in the amount of steel used. Whereas ordinary reinforcing steel is designed for a stress of about 30 tons/in^2, the wires or cables for prestressed concrete have a working tension of 90 tons/in^2.

The transformation of concrete from a somewhat brittle and uncertain material into a tough and highly resilient material is well illustrated by the change in the characteristics of common structural elements like planks and posts, whose normally unyielding nature and tendency to break under quite small deflections is a familiar fact. Prestressed examples of these elementary structures, on the other hand, have an astonishing resilience under load, and maximum deflections to be measured in inches for the unprestressed structure are, for the prestressed element, to be measured in feet.

M. Freyssinet's method then is to use a comparatively thin layer of concrete that, by reason of its resilience, bends under heavy loads thus forcing the subgrade to take a substantial part of the load locally and more or less directly. The concrete layer is not expected to spread the load very much beyond its point of application, with the consequence that quite considerable pressures—of the order of 25 lb/in^2—have to be taken by the subgrade directly under the load. Where the ground can easily be consolidated to take this kind of pressure, as at Orly and Heath Row, there is no doubt of the advantages to be gained by M. Freyssinet's method. Whether it would be successful on other sites, with subsoils much inferior in natural firmness to those at these two sites, is open to question. What is not open to question is the undoubted advantages to be gained by the proper exploitation of prestressed concrete.

The details of the scheme adopted by M. Freyssinet for putting the principles above described into operation are of great interest,[1] but will not be discussed here.

The French engineer's basic approach to the problem of coping with heavy runway loads has been briefly described here for two reasons. It provides a useful background against which to assess the merits of the water-borne runway which also makes use of the same kind of flexible concrete 'carpet'.

The essential difference between the two schemes is that, whereas Freyssinet lays his carpet directly on the ground, the author proposes to lay it on a number of very shallow rubber water-bags. This difference has a profound effect on the forces exerted on the ground underneath the carpet and also has some effect on the carpet itself. In the matter of ground forces, Freyssinet's concrete carpet transmits the heavy runway load directly to the ground beneath, so that there is a maximum pressure directly underneath the load, the value of this maximum depending on the flexibility of the carpet. In the water-borne runway, on the other hand, the ground pressure is necessarily equal to the uniform hydrostatic pressure in the particular water-bag that happens to lie beneath the load, and the value of this pressure is inversely proportional to the area covered by the bag. Thus, whereas in Freyssinet's method the only way to reduce the maximum pressure is to use a thicker carpet so as to reduce the local peak pressure, in the water-borne runway the pressure can be made as low as need be by merely increasing the area of each bag.

Fig. 1 illustrates these differences very well. At (a) we see Freyssinet's carpet under the concentrated load P, and at (c) the same load applied to the water-bag supported carpet. At (a) we see the local depression made in the ground and at (b) the corresponding pressure distribution extending over a circular area of diameter AB, and having its peak value P_1 at the centre. At (c) we again see the deflected carpet, but this time there is no corresponding depression formed in the ground beneath; the deflection is accommodated by an equal deflection of the thin top-surface of the bag. The ground beneath the under-surface of the bag EF is uniformly loaded by the (comparatively) light hydrostatic pressure P_2 represented by the load P divided by the area of the bag. Thus, in the matter of ground pressure, the water-borne concrete carpet is immeasurably superior, but it suffers the disadvantage of receiving less local support underneath the load than it does in the French scheme, and on that account has to be stronger.

The situation as between the two schemes may perhaps be best summarized by saying that, at the cost of using a somewhat stronger carpet and of facing the expense and complication of the water-bags, the water-borne runway has the following basic advantages over Freyssinet's scheme.

(1) It enables a runway to be built on the poorest soil so as to be capable of carrying the heaviest loads—in theory there is no limit to the size of aeroplane that could be accommodated.

This follows from the fact that, by eliminating the soil underneath the bags as a relevant factor in the construction, the problem becomes largely a mechanical, rather than a civil, engineering problem. It is one of designing a concrete carpet to withstand loads—the landing loads and the supporting water pressure—that are known with precision.

(2) As a corollary to (1), it makes it possible to build a runway for the heaviest traffic in places where its construction by Freyssinet's or any other method would be out of the question.

(3) It requires no ground reinforcement, but only a reasonably smooth surface. Indeed, so far as ground reinforcement is concerned, a runway of this type, capable of carrying a 100 ton aeroplane, could feasibly be laid down on soft, pasture land directly and with very little preparation. The use of 20 ft. square bags would reduce the 50 ton load at each undercarriage to the wholly innocuous pressure of 2 lb/in^2, which may well be compared with the 12 lb/in^2 foot pressure of an average man.

(4) It makes possible the construction of temporary runways, the subsequent removal of which leaves the site little the worse, and makes the materials of construction—the slabs and the water-bags—available for use elsewhere.

(5) It cuts out the necessity for a careful study of the soil-mechanics of a proposed site and the use of pilot experiments over extended periods to test seasonal changes.

(6) It makes the design of the concrete carpet more of an exact science, because the operational conditions can be defined much more accurately. The concrete slabs forming the carpet can be tested in the laboratory under conditions closely simulating the actual field conditions, since the applied loads, as well as the supporting hydrostatic pressure, will be known with considerable precision. Moreover, as the load-carrying capacity of the soil under the bags is not a parameter in the problem, a tentative design can be tested quickly and cheaply by means of a model.

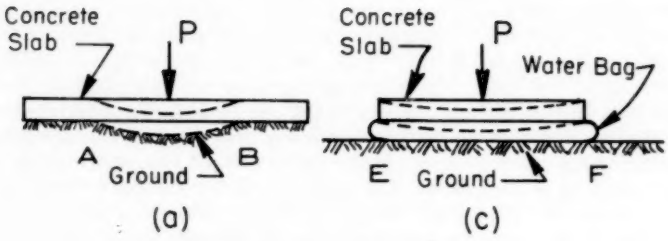

Concrete Slab
P
A
B
Ground
(a)
Concrete Slab
P
Water Bag
E
Ground
F
(c)
DEFLECTION
Pressure
P1
(b)
Pressure
P2 (Uniform)
(d)
PRESSURES

Fig. 1

This is out of the question when the quality of the sub-soil is the major parameter in the problem, for no amount of ingenuity in the laboratory can hope to represent the complex behaviour of soil, which demands full-scale field experiments or nothing.

(7) The mounting of the concrete carpet on a layer of water-bags eliminates one source of trouble, the avoidance of which is a major design problem in any other type of runway construction, including Freyssinet's. This refers to the effect of a rapid change of air temperature causing the concrete to expand or contract according to whether the temperature rises or falls. As the ground change of temperature lags behind that of the covering concrete, a differential expansion or contraction takes place with the result that high stresses can be induced in the concrete. The contraction of a 50-yard wide runway under a temperature drop may well induce a movement of the edges toward the centre of as much as a couple of inches, and if this is prevented by ground friction the tensile stresses set up may easily exceed the prestress and so cause cracking of the concrete even if permanent damage is avoided. The more or less unrestricted movement of the water-supported concrete solves this problem.

(8) However heavy and frequent the traffic on a water-borne runway, the ground underneath the bags remains unaffected being completely insulated by the water layer from all the 'wear and tear' suffered by the concrete above. This means that local damage to the carpet can be repaired expeditiously by putting in new slabs for old without touching the ground underneath. Craters formed by enemy action need only to be filled in and the surface levelled before covering it with new bags; for the hydrostatic pressure is easily withstood by the fresh soil in the crater.

(9) The principle of the water-borne runway can be turned to account in directions other than that of solving the landing load problem of future very large aeroplanes. It can be used for roadways and particularly for temporary roadways intended to cope with excessively heavy loads, for beach operations in war, for temporary landing strips used either for civil or military purposes where rapidity of construction (and subsequent dismantling) is a major factor.

(10) For some of the purposes mentioned in (9) other and lighter materials than concrete could be used with advantage. Built-up slabs of cheap softwood, with steel fittings, for example, would facilitate transport and repeated assembly and dismantling.

These are some of the advantages to be gained by the adoption of this unorthodox method of runway construction. They have however to be paid for by the extra complication and expense of the rubber bags, although in the matter of expense, what is saved on subgrade preparation and construction may well make up for the cost of the bags.

Brief Account of Work Done up to the Present

After conceiving the idea of a water-borne runway,* the next step was to examine the constructional implications of the scheme and to appreciate as

*The theoretical aspects of the problem are discussed in R.A.E. Technical Note No. Structures 34.(1)

clearly as possible the problems to which they gave rise. This meant the carrying out of a number of approximate calculations, upon completion of which it was thought desirable to confirm some of the conclusions reached by carrying out laboratory tests on a small scale model of a strip of water-borne runway.*

This model, photographs of which are shown in Figs. 7, 8, and 9 was, in spite of its modest dimensions, intended to demonstrate—

(a) The efficacy of the proposed method of connecting together the individual square slabs forming the concrete carpet.
(b) The pattern and amount of the deflections of the slabs under an increasingly-heavy load successively applied in the centre of a slab, at a common edge of two adjacent slabs, and at a common corner of four slabs.
(c) The corresponding stresses induced in the slabs.
(d) The general firmness and solidity that may be expected from this kind of water-supported runway.

The results of this test, which is described more fully in paragraph 2, and in quantitative detail in the Appendix, proved very satisfactory. The efficacy of the general arrangement of slab connection referred to in (a) was proved, and the deflections and stresses mentioned in (b) and (c) when translated in terms of a full-scale runway were such as to appear acceptable. What was most gratifying about the result however was the behaviour of the model under item (d). The impression gained in walking on the model strip was that, in the matter of firmness and solidity, it vied with the concrete floor of the laboratory on which it was mounted.

Model Experiment

A diagrammatic plan view of the model is shown in Fig. 2. The 2-ft. square, 1-inch thick slabs are made of wood, and connected together with thin steel tongues, so creating an articulated joint capable of transmitting shear but not bending actions. Each slab rests on its own 2-ft. square, 3/4-inch deep water bag made of thin rubber-dinghy material. Photographs of these elements are shown in Figs. 7, 8, and 9. The purpose of connecting the slabs together by joints capable of transmitting shear alone is two-fold; it facilitates the removal of a slab, either for inspection of the bag underneath or for the fitting of a new slab or bag, and it helps to keep the bending moment of the same sign throughout the loaded slab. The latter feature simplifies the design of the slab and tends to keep the water pressure near its nominal value.

Boundary Stiffeners

It was realized that, owing to the continuous interconnection of the slabs, one slab cannot tilt without at the same time tilting adjacent slabs, which in turn affect slabs still further away, the final result being a quilting of the whole surface. To prevent this the outer boundary of the strip was constrained in the first test to remain approximately straight by reinforcing it with four stiff continuous members. Under the most unfavourable conditions, i.e. with the concentrated load applied at a common corner O, the deflection produced by a 1000 lb. load was 0.2 inches. Thus, if the 2-ft. slabs are regarded as

*Work described in R.A.E. Technical Note No. Structures. 75.[2]

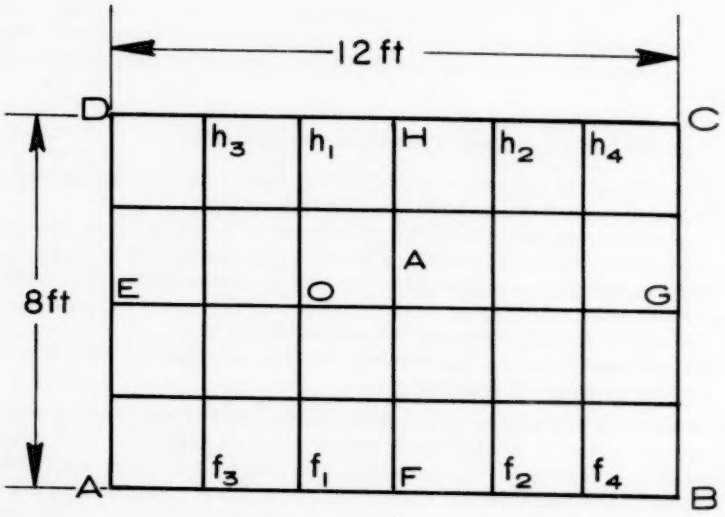


Fig. 2

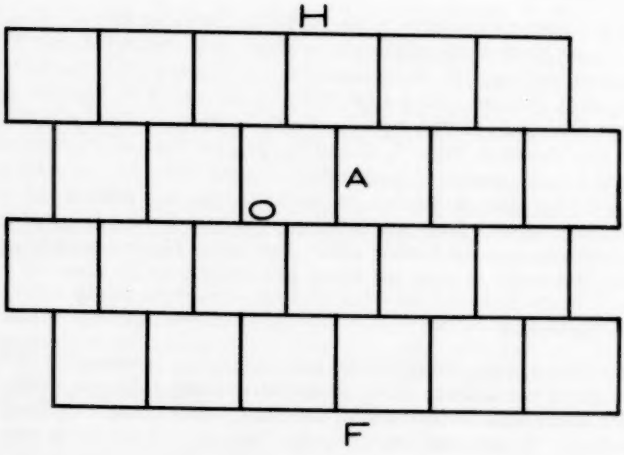


Fig. 3

1/10 scale models of 20-ft. slabs, the full scale deflection would be 2 in. under a load of 100,000 lb.—a not unsatisfactory figure for a first attempt.

Removal of Boundary Members

In order to see how much of the resistance to deflection was due to the boundary-stiffening members, these were removed and the previous loading test repeated. Before applying the load however it was observed that walking over the strip gave the same impression of firmness and solidity as before, which was a little surprising. Even more surprising was to find the measured deflection still comparatively small although double the previous value. The explanation turned out to be that the imperceptible tilting common to all the slabs was taking place in each about an axis slightly offset from the center of gravity of the slab, thus entailing the doing of work against gravity.

Benefit of Staggered Slabs

The strip was next dismantled and the four rows of slabs arranged to give a staggered pattern as in Fig. 3. Comparing the effect of applying a load at A in the two cases, one can see that, whereas in Fig. 2 it is possible to produce a continuous valley from F to H, in Fig. 3 this is impossible, for any sinking along the edge A is strongly resisted by the bending stiffness of the adjacent slabs in the adjoining rows. The anti-tilting property of the staggered arrangement is well demonstrated by the fact that, in spite of the continuity of the longitudinal joints, the deflection produced at O in Fig. 3 was some 30% smaller than that at O in Fig. 2 with boundary members present.

Hexagonal Slabs

It is unfortunate that square slabs cannot be staggered in both directions at the same time, but it is possible, by using hexagonal slabs to achieve stagger in all directions. Any tendency of a common edge such as AA' in Fig. 4 to sink under load is immediately blocked by the resistance of the adjacent slabs against bending along the dotted lines. Although hexagonal slabs were not tried, there is little doubt that their use would do away with the need for any other anti-tilting agency.

Design of Inter-Slab Shear Joints

In preparation for a full-scale test with prestressed concrete slabs, some attention was given to the design of inter-slab joints that should not only possess the required strength but also be easily dismantled for the purpose of removing a slab. The customary type of steel dowel, apart from the difficulty of dismantling, was thought to be unsuitable for the heavy duty contemplated for these joints. A few attractive schemes were suggested by Mr. T. N. Sparkes and his staff at the Road Research Laboratory but, as the prospect of carrying out even a restricted full-scale test receded, no more than a few preliminary experiments were made.

An alternative scheme of integrating individual slabs into a complete carpet, and one that holds out high promise, has been suggested by Dr. P. B. Morice and Mr. G. H. Cooley of the Research and Development Division of the Cement and Concrete Association. The idea behind the scheme is to look upon the prestressing problem and the problem of effectively interconnecting the individual slabs as a single problem.

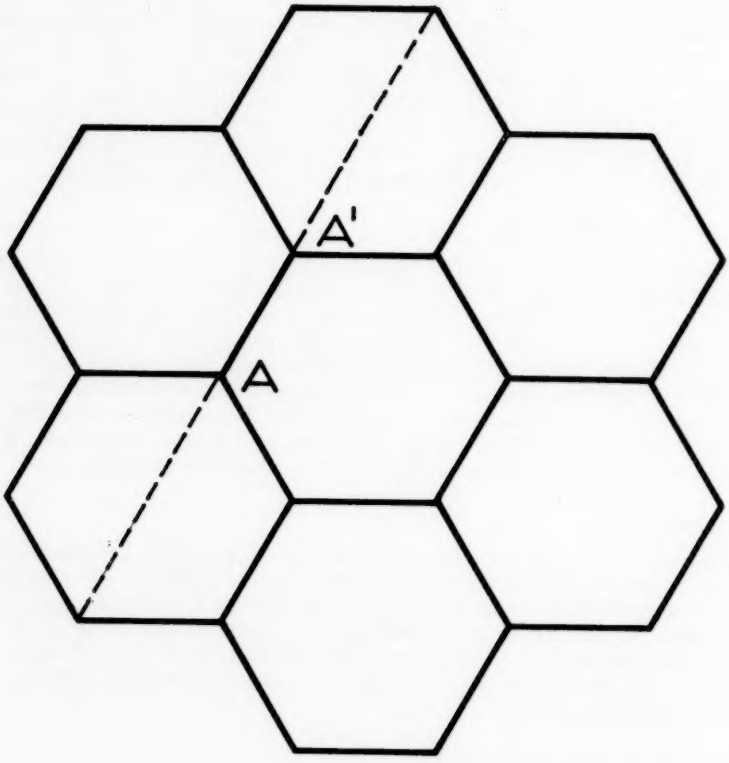


Fig. 4

The prestressing of a single slab of some 20-ft. square is open to the objection that the amount of cable stretch it entails is rather small, with the result that even a slight amount of creep in the cables has an appreciable effect on their tension. By prestressing the slabs in pairs, however, every cable has a length equal to that of two slabs, and a small amount of creep has only half its previous significance. Moreover, the important further advantage is gained of doing away with the complicated shear-carrying joints, each slab edge now butting hard up against that of its neighbour. Fig. 5 shows at a glance the principle of the method. It shows a series of four slabs (whose thickness is much exaggerated relative to their lengths) which butt hard up against one another at B, C, and D. The slab-pair A'B and B'C is prestressed by the cable A'C shown by the full-line, the pair B'C and C'D is similarly prestressed by the cable B'D shown by the dotted line, and the last pair C'D and D'E is prestressed by the full-line cable C'E. Thus each slab is prestressed in the same direction by two sets of cables, one connecting it to the slab on its left and the other to the slab on its right. A similar arrangement operates in a direction at right angles to that shown, so that each slab is securely fastened to the four slabs surrounding it.

The pressure with which the slabs are forced together by the prestressed cables precludes the possibility of the butting faces sliding vertically on each other under shear loads. This has been proved by a test[3] carried out in the laboratory of the Cement and Concrete Association (see Appendix).

It can be seen from the above description that large areas, of the order of 150 ft. by 300 ft., can in this way be covered by what amounts to a monolithic carpet of concrete, and moreover without sacrificing the practical advantage of being able to remove an individual slab at will, by detaching the four sets of cables that join it to its four neighbours.

It is worth pointing out that, once this type of construction is accepted, there is no need to relate the size of the water bags to that of the slab elements, and therefore bags of larger area can be used. This has an important bearing on the load that can be carried. For suppose that, with 20-ft. square bags, a concrete carpet can take a 200-ton aeroplane (100 tons per undercarriage), the ground pressure being thus 4 lb/in^2. By using 28-ft. square bags and increasing the concrete thickness 40% the load that can be carried is doubled, so that the runway can now take a 400-ton aeroplane.

This may seem mere simple arithmetic. It is however more than that; for this elementary example shows that, without changing the amount of rubber used (there is a slight drop in fact due to the smaller perimeter for the same area of bag) and without increasing the ground pressure, a jump into a bigger size-class of aeroplane can be made for the cost of a 40% increase in thickness. Moreover, the behaviour of the new carpet under the new load is calculable with precision. In any other type of runway this sort of jump could only be made by a much more extensive treatment of the subgrade foundation. This becomes necessary because the heavier load penetrates deeper, as it were, into the soil.

Amount of Concrete and Steel Involved

If the above method were adopted, a 100-ton aeroplane could be carried on a concrete carpet not more than 8-in. thick. This is based on a prestress of 1000 lb/in^2 which, in conjunction with the figure for the slab thickness, gives some idea of the amount of high-tensile-steel cable required.

Fig. 5

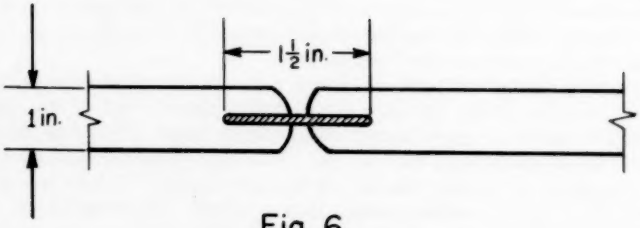


Fig. 6

The maximum deflection under these conditions is estimated at less than 1/2 inch.

Problem of Water-Bags

The main drawback of the water-borne runway is the expense of the water-bags. It seems that a 20-ft. square rubber bag 5 inches deep will cost anything between £60 and £90, so that a runway 50 yards wide and 2000 yards long would require an expenditure of something like £200,000. There is some comfort however in the fact that the cost is practically independent of the size of the aeroplane that is to use the runway—whether it be 100 tons or 1000 tons.

Regarding the probable life of the rubber bags, a considerable amount of research has been done by the British Rubber Development Board in gathering data on this point. It appears from this that there are plenty of cases where rubber articles are still serviceable after 50 to 70 years. Rubber, as is well known, lasts best when stored in darkness and excluded from air. The rubber bags will certainly be in darkness and will also, owing to being pressed against solid surfaces on both faces by the water pressure, be largely out of contact with air.

It is again emphasized that the essential quality in the material for the water-bags is that it should be water-tight and that it should remain water-tight. It does not have to be extensible, nor need it be even flexible except for the shallow vertical walls of the bag. The extensive top and bottom surface of the container, being completely unstressed except for the mild compression stress of the order of 4 lb/in^2 from the water pressure, could be made of practically any water-tight material, and it is unfortunate that in using rubber one has to pay for qualities that are not exploited.

Present Position

The principle of a water-borne runway of the type above described has been discussed by various bodies, certain Committees of the Aeronautical Research Council among them, and pronounced sound. What is uncertain about the scheme, as the A.R.C. bodies have rightly pointed out, is its feasibility as an economic proposition. It has however been recognized as possibly a valuable scheme in the event of a runway having to be built either on poor soil or not at all.

A direct comparison, on the basis of the amount of concrete and steel used, between a prestressed concrete carpet laid on water-bags and one laid directly on the ground is difficult to make. This is because of the number of parameters that must govern any such comparison. Suppose, for example, that the subsoil is capable of withstanding a pressure of 25 lb/in^2 and that, in order not to exceed this pressure, a 6-in. thickness of concrete is required if laid directly on the ground. The corresponding thickness of a water-borne runway depends on the size of water-bags used. It would be sheer waste of concrete to use a size capable of limiting the hydrostatic pressure to 3 or 4 lb/in^2 when the soil can stand 25 lb/in^2. The proper procedure is to reduce the area under each bag to a figure that makes the hydrostatic pressure 25 lb/in^2. If this is done, the thickness of the concrete carpet is correspondingly reduced and should then be little, if any thicker that that for a carpet laid directly on the ground.

The advantages of the water-borne runway are, however, least conspicuous when the subsoil is much above average in strength, and the weaker the soil

the more obvious these advantages become. For if a concrete carpet is laid directly on weak soil it is likely that, although the concrete may receive adequate support from the soil at first loading, this is only at the cost of forming a permanent depression which at subsequent loadings gives no support to the concrete until, so to speak, the slack is taken up. Such free movement of the concrete under load and the violence with which it is stopped must lead eventually to serious deterioration. It may be argued that, in such a case, the remedy is to use a thicker carpet, to make it as thick, if necessary, as that required for the water-borne runway. The answer to that argument is that no amount of thickening the concrete can prevent the loading on the subsoil from being concentrated under the applied load; hydrostatic loading alone can prevent that.

The above remarks are sufficient to indicate that no facile quantitative comparison can be made between the thicknesses of concrete required for the two types of construction, and that this is only possible when all the governing factors are well defined.

As to the construction of a runway on the water-borne principle, the calculations made, in conjunction with the small-model experiment carried out, indicate that there do not appear to be any serious difficulties. The logical next major step is clearly to carry out a much more ambitious test, that should not only provide a real check on the magnitude of the constructional difficulties but also allow the behaviour of the water-supported concrete carpet under actual landing loads to be observed. A 50-yd. length of water-borne runway inserted in an existing runway would provide all the data required. Certain preliminary tests would naturally be necessary for checking the adequacy of various structural elements, but they would be subordinated to, and governed by, the main test.

Such a test would not be cheap, and for the moment it has been decided not to embark on it.

Part II — Model Experiment and Other Tests

A brief description is given here of the model experiment* that was carried out, and the results of other relevant tests are given.

Description of Model

A one-tenth scale model (in plan form) has been built in which the 20-ft. square concrete slabs are represented by 2-ft. square wooden planks one inch thick, the under side of each of which is covered by 3/8-in. steel sheet screwed on loosely to add weight. Connection between one plank and the next is made by a thin steel tongue 1-1/2 in. wide, 20 S.W.G., fitting into grooves in the sides of the planks as shown in Fig. 6, to form a shear-carrying joint. Each plank unit weighs about 80 lb. and 24 units are connected together to form a rectangular strip 8 ft. wide by 12 ft. long. Under each plank unit or slab is placed a thin-walled rubber bag of the same size, 1 inch deep and filled with water to the exclusion of all air, the quantity of water in each bag being the same.

To complete the model, a light continuous wooden frame (section 1-3/8 in. wide by 2-1/4 in. deep) is firmly fixed around the edges of the rectangle to

*First described in R.A.E. Tech. Note No. Structures 75 June, 1951.

form a boundary reinforcement for stabilising purposes.

The photographs of Figs. 7, 8, and 9 show respectively the tongue-and-groove joint; the (filled) water bag, and the complete unit of 24 slabs with its reinforcing boundary frame. Fig. 9 also shows a load of 1000 lb. being applied via a small tail wheel to the common corner of four adjacent slabs. The method of measuring deflections and strains can also be observed in this photograph, deflections being measured relative to the laboratory floor by means of dial gauges, and the stresses in the slabs by means of resistance strain gauges, the necessary amplifiers for which are seen mounted on a portable tubular frame in the background.

Test Procedure

At each loading vertical deflections were measured at every corner of every slab, and, as the number of dial gauges was not sufficient to enable simultaneous measurement to be made at all points, recourse was had to repeating the loading.

Strain gauges were only fitted to those slabs lying nearest to the point of load application and to a few points on the boundary-reinforcing member. The precise location of the gauges is shown in Fig. 10.

The load was applied by means of shot-bags piled on a platform carried on the end of an extensible frame and resting on a small tail-wheel. Two upright supports with their feet just clear of the surface stradle the wheel so as to take the load in the event of a tyre burst. A pulley tackle hung from the roof enabled the load to be applied and removed with equal facility.

The unit was tested for three positions of the applied load which are marked (a), (b), and (c) in Fig. 10.

Results Obtained

Before any quantitative tests were carried out some idea of the behaviour of the model was gained by walking on it. The general impression was of firmness and solidity comparable with the concrete floor on which the model rested.

Subsequent measurements showed that deflections and stresses varied approximately linearly with the load applied, but their distribution changed a little with the magnitude of the load.

Details are given, numerically in Figs. 11, 12, and 13 and pictorially in Figs. 11a, 12a, and 13a of the deflections and strains corresponding to a load of 1000 lb. applied at positions (a), (b), and (c) (Fig. 10) respectively.

The numbers enclosed in squares give the deflections in thousandths of an inch from the unloaded datum position, while the other numbers give the surface stresses in the slabs and boundary members (based on measured strains and an assumed E of 1.5×10^6 lb/in^2). The slab strains were measured at the central points of the slabs and are represented by positive or negative stresses according as the strains are tensile or compressive.

The second diagram in each figure shows, in isometric projection, and to a suitable scale, a "bird's eye-view" of the displacements of the surface of the model runway, from the original plane. From this the general character of the deformation can readily be appreciated.

Discussion of Results

Fig. 21a is perhaps the simplest case to discuss. Here the load is applied midway along the common edge of two slabs and, as expected, the maximum

Fig. 7 Method of Assembly of Panels

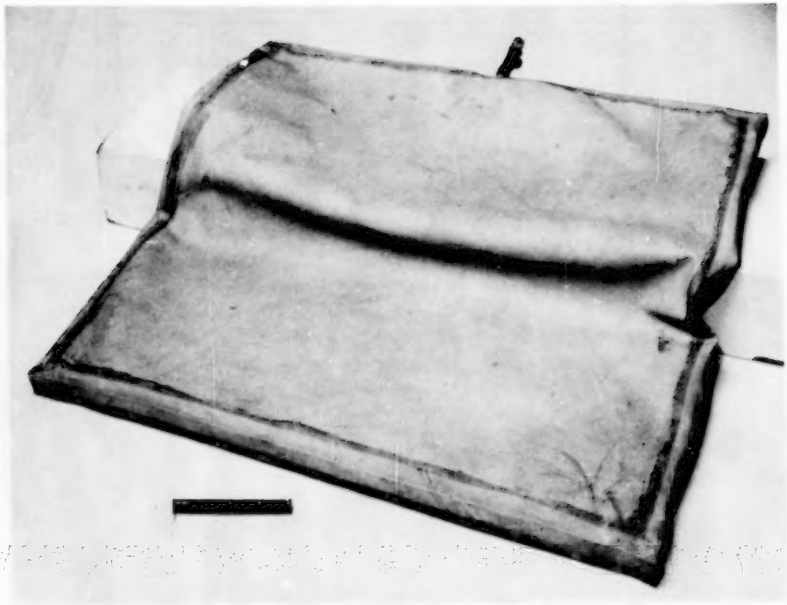


Fig. 8 Showing Rigidity of Sides of Water Bag

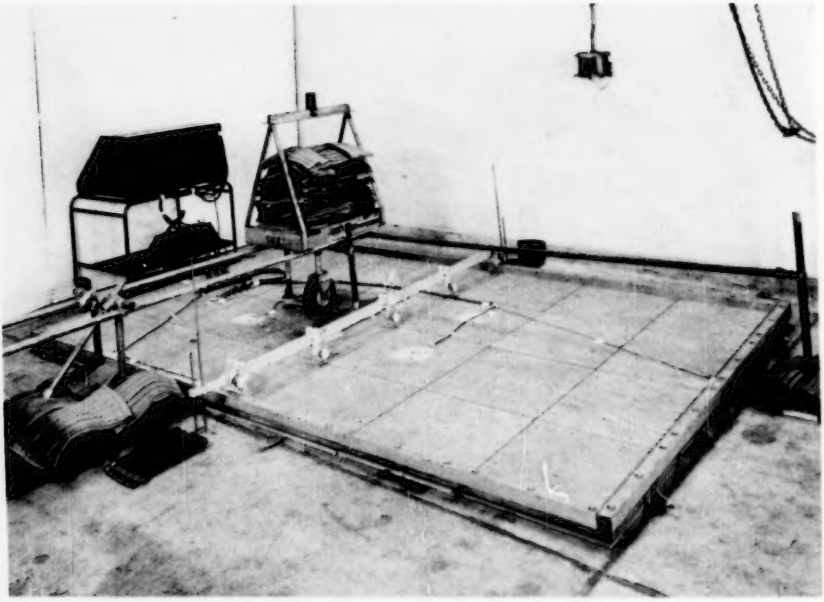


Fig. 9 Model Loaded at Junction of Panels 16, 10, 11, and 17

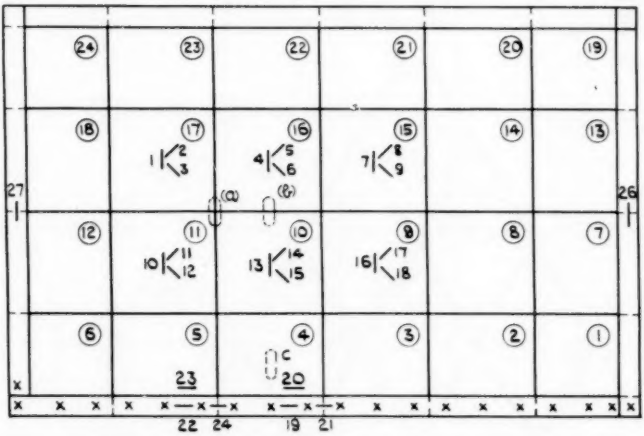


FIG.10. PANEL REFERENCES, LOCATION OF STRAIN GAUGES & LOADING POINTS (a) (b) & (c)

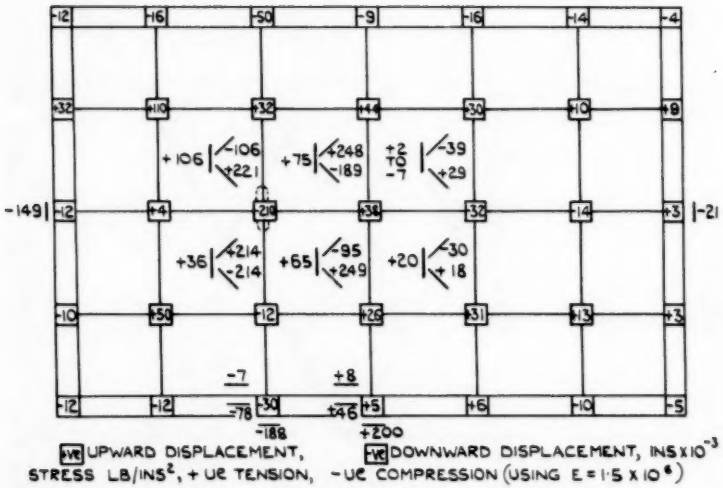


FIG.11. 1000 LB LOAD APPLIED AT JUNCTION OF PANELS 16. 10. 11. 17.

FIG. 11a. 1000 LB. LOAD APPLIED AT JUNCTION OF PANELS 16. 10. 11. 17. (REF. FIG. 10.)

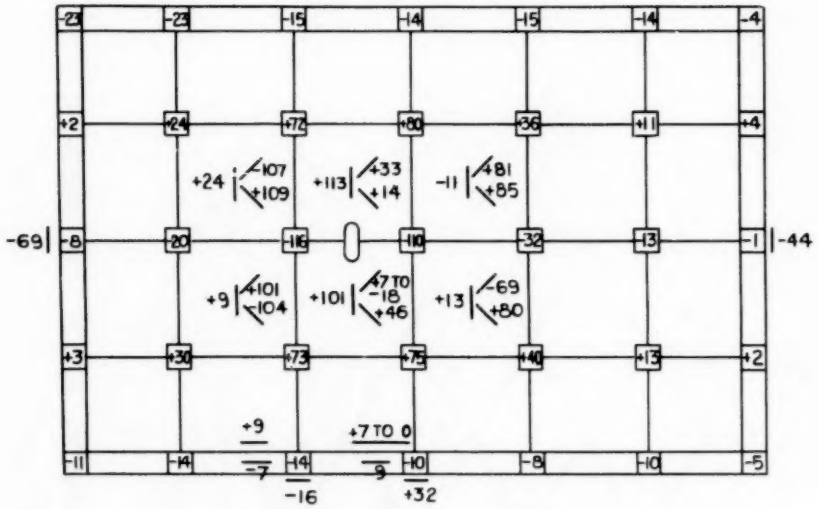
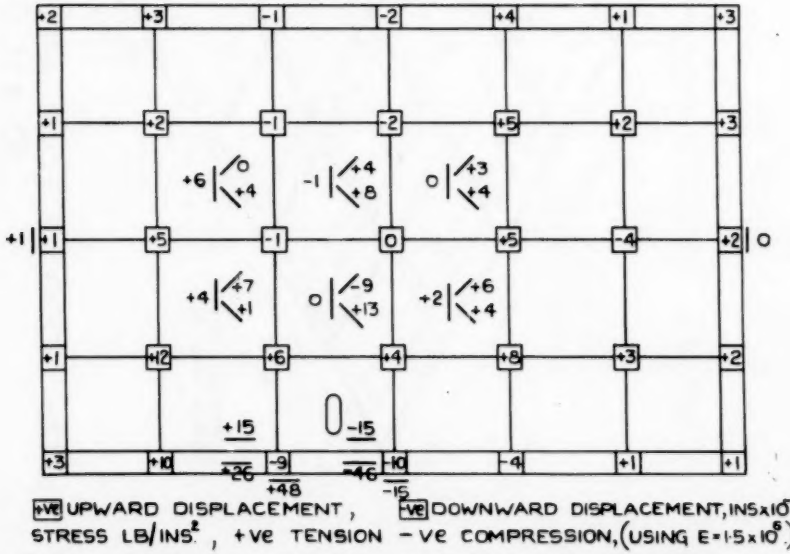


FIG.12. 1,000 LB. LOAD APPLIED AT COMMON EDGE OF PANELS 10 & 16.



+ve UPWARD DISPLACEMENT, -ve DOWNWARD DISPLACEMENT, INS x 10^{-3}
STRESS LB/INS^2, +ve TENSION -ve COMPRESSION, (USING E = 1·5 x 10^6.)

FIG.13. 1,000 LB. LOAD APPLIED AT CENTRE OF PANEL 4.

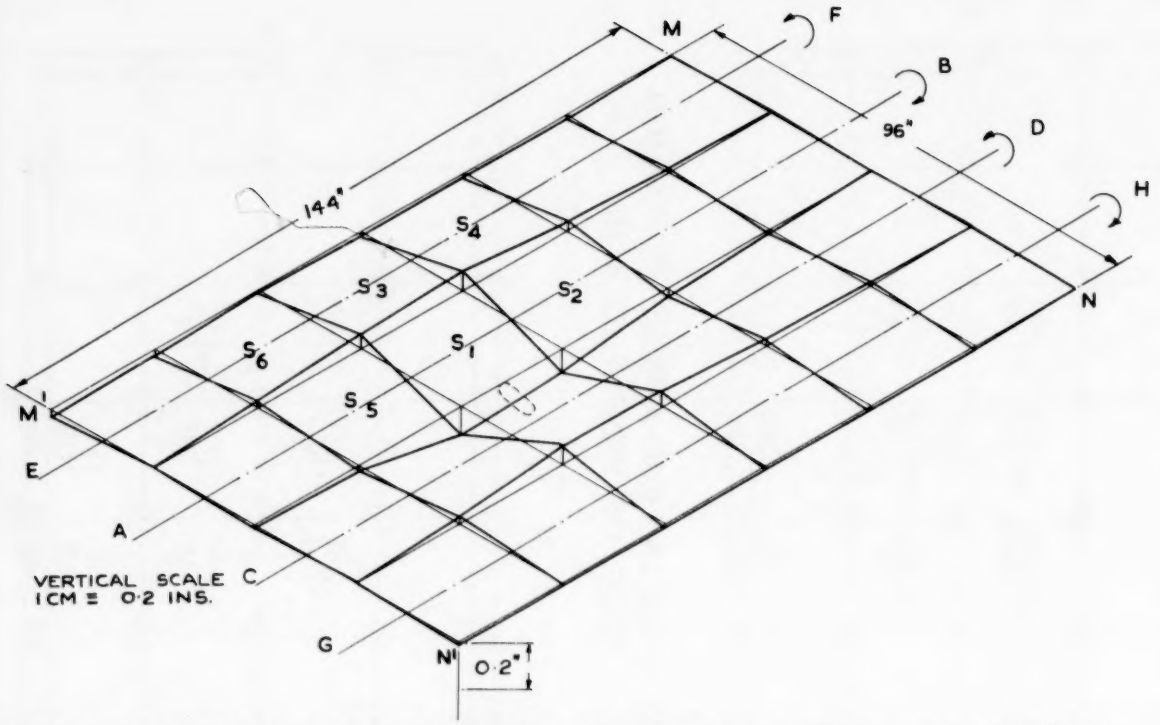


FIG. 12a 1,000 LB. LOAD APPLIED AT COMMON EDGE OF PANELS 10 & 16 (REF. FIG. 10)

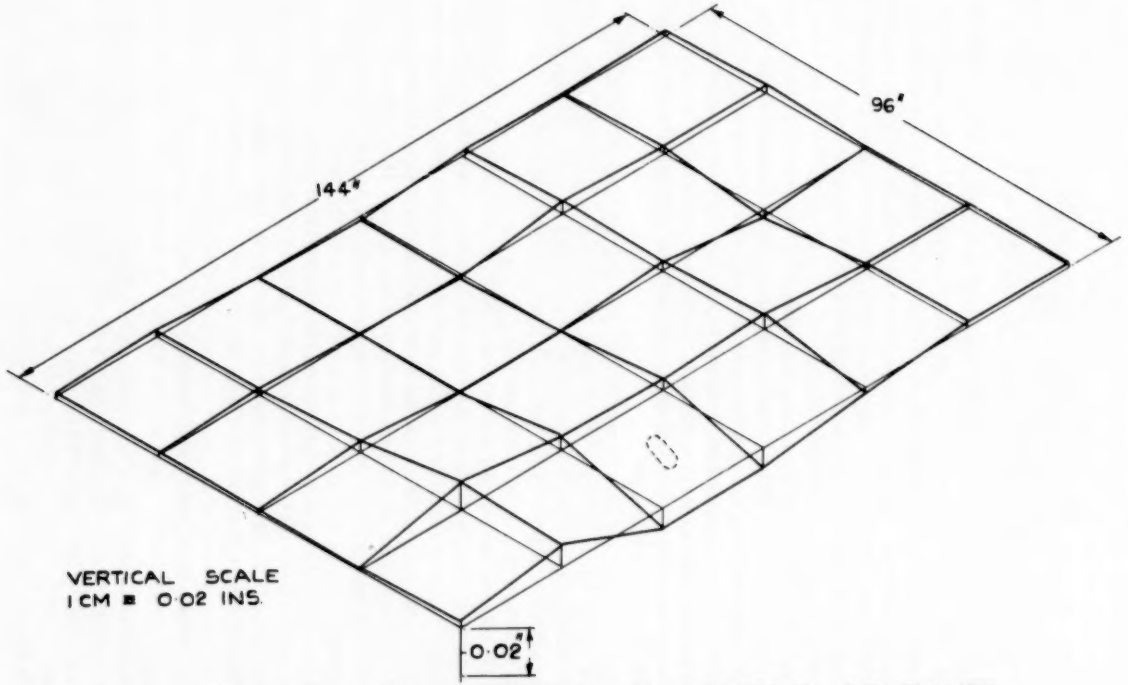


FIG. 13a. 1,000 LB. LOAD APPLIED AT CENTRE OF PANEL Nº 4 (REF. FIG. 10)

deflection occurs along that edge over which it is fairly constant. The tendency of course is to form a valley along that edge and its continuation to the two opposite boundaries, but, if the slabs were rigid, this tendency would be almost wholly neutralised by the stiffness in bending of the boundary members MN and M'N'. As it is, however, owing to the flexibility of the slabs, slab S_1, for example, is able to tilt about the axis AB as a result chiefly of the twisting and tilting of the slabs adjacent to it—S_2, S_5, and S_3—but partially of the bending of slab S_1 itself.

Considering that half of the surface bordered by the edge MM', one can easily follow the path along which the load is transmitted to the boundary. Slab S_1, under the offset load applies a torque about the axis AB to all the slabs lying in that row. By lifting the adjacent edge of S_3 it sends another torque of about the same magnitude (judging by the deflections produced) but opposite sign along the row EF, to be neutralised as in the case of the other torque, at the boundary members.

It was found possible, by assuming a reasonable value for the shear modulus of the wood (1.5×10^5 lb/in^2) and by assuming some reinforcement by the steel sheet* screwed to it, to reconcile the torque actually applied (by the offset load) with that transmitted as deduced from the measured deflections and strains. The deformation of the surface must, in other words, be attributed to the cumulative effect of the individual distortions of the slabs partially in bending, but chiefly in torsion.

The same effects may be noticed in Fig. 11a except that there the displacements are greater at the point of load application. This is to be expected from the tendency in this case to produce two valleys at right angles to each other. The effect of superposing two such sets of corrugations is to produce a resultant corrugation along the diagonals.

It is to be noticed in this particular case that the deflection at the load is somewhat greater, in comparison with the surrounding deflections, than in the previous case. This is attributed to the unfavourable situation of the slabs in relation to the load, in that each of the four slabs concerned has to resist one quarter of the total applied load by bending at the corner where the slab, acting as a beam along its diagonal, has comparatively only a small cross-sectional area.

Turning to Fig. 13a, which represents the case where the load is applied at the central point of the slab, one notices that, although the load is felt throughout all the other slabs, the deflections are only some one-tenth of those for Fig. 11, and are never greater than 0.01 in.

Conclusions Drawn from the Model Tests

Rubber Bags

As regards the rubber bags, the tests have shown that their behaviour under load exactly fulfills expectations. Friction between the under surface of the bags and the floor and between their upper surface and the slabs has been adequate to inhibit any tendency for lateral spread. The shallow walls forming the edges of the bags have also proved to be effectively inextensible.

*The stiffness of the steel sheet was largely ineffective because of its flimsy connection—one woodscrew in the centre and one at each corner—to the wood slab.

The bags in fact would have been quite satisfactory under much higher pressures than the 2 lb/in^2 which was the maximum pressure used in the tests.

Amount of Applied Load

As the 2-ft square slabs represent 20-ft. slabs full-scale, thus giving a linear scale of 1/10, the applied load of 1000 lb. represents 100,000 lb. full scale, i.e. 45 tons, or the static load at one wheel unit of a 90 ton aeroplane. The water pressure is of course the same as in the model, i.e. 2 lb/in^2.

Surface Deflection Under Load

Apart from the case where the load coincides with the corner junction of 4 slabs, the greatest deflection measured was 0.1 in., which represents 1 in. full scale—a comparatively small deflection in a 20-ft. slab. With the load at a corner there is some local bending of the slab which increases the deflection at the corner to 0.2 in. (2.0 in. full scale). It is to be noted, however, that the internal construction of the slabs (already described) is in no way representative of the full-scale construction, which will be of reinforced concrete. Most of the deflection in the model is due to twisting of the slabs, an action which owing to its low shear modulus, wood is peculiarly unsuitable to resist.

It is to be expected, therefore, that full-scale deflections will be considerably smaller than those suggested by the model test results.

Stresses

As can be seen from Figs. 11 and 12, the stresses are all quite small. Moreover the measured strains from which they are deduced are found to be reasonably consistent with the measured vertical deflections.

Part Played by Boundary Members

In the tests described above immunity from relative tilting of the slabs was ensured by the fitting of boundary-stiffening members round the periphery of the rectangular strip of runway. This was considered necessary because the only other obvious stabilising factor—the gravity resistance of the water against tilting of its surface plane—was clearly inadequate for the purpose.

It appears however, in the light of further experiments, that another stabilizing factor, originally thought to be negligible, plays an important role in resisting deflection under load. This is the fact that a slab does not always tilt about an axis through its centre, i.e. through its centre of gravity, but rather about a parallel axis a little displaced from the c.g. in the direction remote from the position of the applied load. It is seen at once that tilting of a slab about any axis other than an axis through its center of gravity can involve doing work, against the weight of the slab. This, indeed, according to experiment, is what actually takes place. The correct representation of gravity foces in the scale model is, on this account, of first importance.

The fact that this aspect of the matter was not fully appreciated in the first tests has two explanations. One is that, with stiffening boundary members fitted, tilting of the slabs is effectively prevented independently of the weight of the slabs. The second is that the gradual dying-away of the deflections with distance from the loading point, although noted, was not associated, as it should be, with lifting of the slabs against gravity. This latter aspect was, however, forced on one's attention as soon as the boundary-stiffening members were removed from the model in the course of the further experiments now to be described.

Effect of Removing Stiffening Boundary Members

The boundary members stiffening the short sides of the rectangular model runway were first removed, and the effect estimated, first by walking on it and next by applying the usual 1000-lb. load at the central joint. To judge by walking on it, the runway felt just as firm and solid as before removal of the stiffeners. The application of the 1000-lb. load however produced a local deflection of 0.3 in., i.e. some 50% than before the removal of the end stiffeners.

The remaining stiffeners were next removed, leaving the strip of model runway entirely unstabilised. Its firmness and solidity under the walking test seemed unimpaired, but the central deflection under load went up to 0.4 in., i.e. twice the deflection registered with periphery fully stiffened. This was a little unexpected, for, without any peripheral stiffening it was thought the slabs would be deflected practically to the floor at the loading point. A quick calculation showed that the tilting of the planes of the water surfaces in the bags could only account for some 5% of the resistance to deflection just found, and it was only when the complete contour of the deflected runway had been obtained by dial-gauge mapping that the part played by the weight of the slabs became clear.

The contour of the deflected runway showed that, with the load applied at the central joint O (see Fig. 14) the maximum deflection was at O, each of the four slabs meeting at O tilting about diagonals perpendicular respectively to diagonals OA, OB, OC, and OD, leaving points G, H, I, and J practically undeflected, but lifting the opposite corners A, B, C, and D almost as much above the original level as point O was depressed below it.

It is however the behaviour of the set of slabs adjoining the central four that is significant. Typical of the slabs in this set are slabs AKEJ and EJDL, which are lifted at A and D under the action of the central group of four. Instead of these slabs tilting about their diagonals KJ and JL, thus depressing the opposite corner E, the latter remain undeflected and formed in effect a fixed pivot. Thus a lifting of the slabs at A and D by an amount δ results in the center of gravity of the slabs being raised (since they are approximately rigid bodies by $\delta/2$).

A simple calculation showed that the work done against the weights of the slabs in this way was not far short of the total work done by the applied load, part of the total, of course, being accounted for by strain energy stored in the slabs themselves.

That some such effect must be present follows at once from the fact of the general die-away of deflections with distance from the point of load application, for this means that one corner or side of a slab lifts more than the other is depressed, and therefore that gravity forces must play a part, either doing work or having work done against them. As the former alternative is inadmissible (since the average level of the slabs cannot fall) the latter must be true, and work is done against the weight of the slabs by the applied load.

Model Representation of Gravity Forces

In the light of the above argument the fact that no serious attempt had been made in designing the model to correctly represent gravity forces stood out. A correct representation demands that gravity loads for the model should, like any other applied load, be reduced in the ratio of the square of the linear dimensions; in other words, the weight of slab per square foot of the model should be identical with the corresponding full-scale figure. In the present

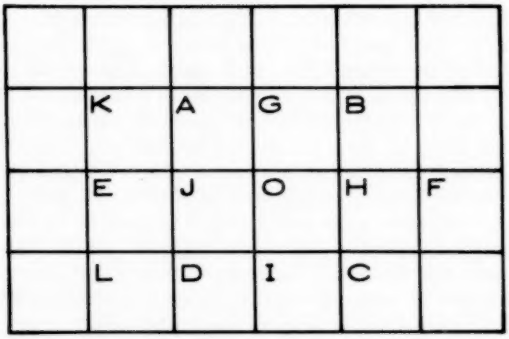


Fig. 14

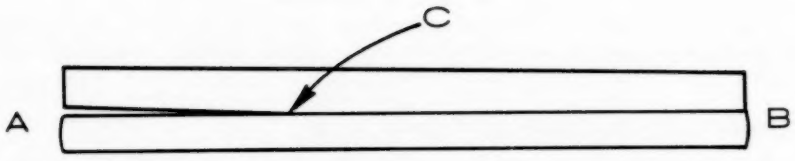


Fig. 15

model the actual weight of the slab proper—i.e. the 2-ft. square wood plank—was only 20 lb. This had been artificially increased to 80 lb. by the attachment of a 3/8-in. steel plate weighing 60 lb. Correct representation, however, requires that each slab should weigh 450 lb.—nearly six times the actual weight used.

As a quick way of checking these views, it was decided to place weights on each slab by increments of 100 lb., taking care to keep the center of gravity at the slab centre. The effect of adding the first hundred-pound was to reduce the maximum deflection from 0.4 in. to 0.25 in. The second 100 lb. reduced this still further to 0.22 in., i.e. to much the same figure as that obtained before removal of the stiffening boundary members. The addition of a further 100 lb. (making 380 lb. in all) reduced the deflection to 0.21 in.

These results suggest that for a given load, the central deflection falls asymptotically to the value obtained with stiffening boundary members in position. The most feasible explanation of this behaviour is that it requires a certain minimum slab weight to maintain uniform contact between the under surface of the slab and the upper surface of the supporting water-bag. Once that minimum weight is reached—in the present case about 200 to 250 lb.—further increase of weight (i.e. gravity loads) has little effect. Fig. 15 shows (on a much exaggerated scale) what is likely to take place when the weight is well below the minimum; contact between the under-surface AB of the slab and the upper surface of the water-bag is maintained over the region BC alone, the region AC being thus unsupported. It is to be emphasized, however, that in the full-scale runway the weight of the slabs (necessary for strength reasons) is such as to ensure that contact is maintained at all points between the two surfaces concerned.

Numerical Results

The variation of the maximum local deflection under a 1,000-lb. load as the gravity load, i.e. the weight per slab, is increased is shown in Fig. 16.

Experiment also confirms the expectation that for a given weight per slab the deflections vary almost linearly with the applied load up to the maximum load.

Variation of Contour Shape with Gravity Loads

So long as the gravity load (i.e. weight per slab) is constant, the contour shape remains sensibly constant and varies only in amplitude under different applied loads. A change in the gravity loads however (with the applied load kept constant) produces a change in the shape of the contour, the change produced by adding 100 lb. to the original 80-lb. weight of the slab being most remarkable. With the unweighted slab one gets a comparatively deep depression at the point of load application which rapidly dies away with distance from that point. With a 100 lb. weight added to each slab, however, the central depression is much reduced while the deflections elsewhere are increased, the tendency being for every slab to tilt about a diagonal by much the same angle. With the addition of another 100-lb. weight per slab, the change already produced in the character of the contour is slightly accentuated, the process of equalizing the tilting angles of the slabs being carried a step further. The final addition of a third 100-lb. merely confirms the expectation that the process of contour change has already practically reached its asymptotic limit, where the slight tilting of the slabs takes the form of a regular

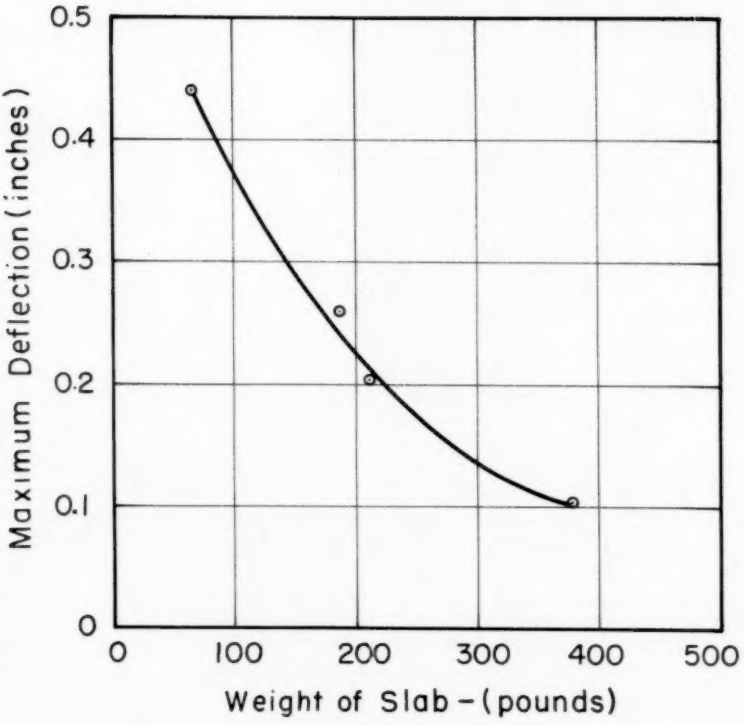

0.5
0.4
0.3
0.2
0.1
0
Maximum Deflection (inches)
0
100
200
300
400
500
Weight of Slab – (pounds)

Fig. 16

geometrical pattern, and where the local deflection at the meeting point of the four central slabs (the point of load application) is greater than elsewhere by reason only of their individual structural deformation.

Conclusions Regarding Boundary Members

The results of the experiments described above, and the physical interpretation of these results that has been here discussed, suggest that a waterborne runway has no need of boundary stiffening members for the purpose of stabilising the slabs against relative tilting under load. In the absence of such members, excessive tilting can only occur when the gravity loads, as represented by the weight of the slabs, are much below what in practice would be a lower limit set by strength considerations.

APPENDIX

Shear Strength of Plain Butt-Joint in a Prestressed Concrete Slab

The following is a brief description of a test carried out by Dr. Morice and Mr. Cooley (already referred to in Part I) in order to see what shear strength can be developed between the abutting faces of two slabs, when the faces are pressed together by the prestressing cables that bridge the joint. Under such conditions the main contribution to the shear strength of the joint derives from the frictional force associated with the normal pressure created by the cables, although the cables themselves, bridging the joint as they do,must come into action before the joint failure develops into a complete break.

Fig. 17 shows a dimensioned sketch (not to scale) of the prestressed concrete test specimen in plan and elevation, the lie of the cables, a section through the joint, the loading diagram, and some details of the cable-anchoring arrangement. The slab is broken across the middle, where the abutting faces are pressed together by the two pretensioned cables A and C, which traverse the whole length of the specimen. Cables D and B help to prestress the two half-slabs but do not contribute to the butting pressure at the joint. They would normally extend beyond the end faces FF' and GG' and, after traversing the adjacent slabs, be anchored on the far sides, thus providing the necessary butting pressure across the end faces.

The shearing force across the joint was applied by two concentrated loads each located 6 in. from the line of the joint as shown in the loading diagram in Fig. 17. As each pre-tensioned cable carried 20 tons the pressure per in^2 across the 1.5-ft^2 joint was:

$$= \frac{20 \times 2 \times 2240}{1.5 \times 144} = 415 \text{ lb/in}^2$$

The first sign of failure occurred at a shear load of 15 tons, and therefore a shear stress of 156 lb/in^2, when some slight spalling of the concrete at the top of the joint became noticeable. The joint failed quietly at about 30 tons (shear stress 312 lb/in^2) by crushing of the concrete, the prestressing cables remaining unbroken. The stress figure at failure represents a friction coefficient of 0.75.

This indicates that, by doubling the prestress, a joint of this type in a 6-1/2 in.-thick slab should be capable of transmitting 10 tons per ft. run without sign of failure. As the load carried by each of two undercarriages of a

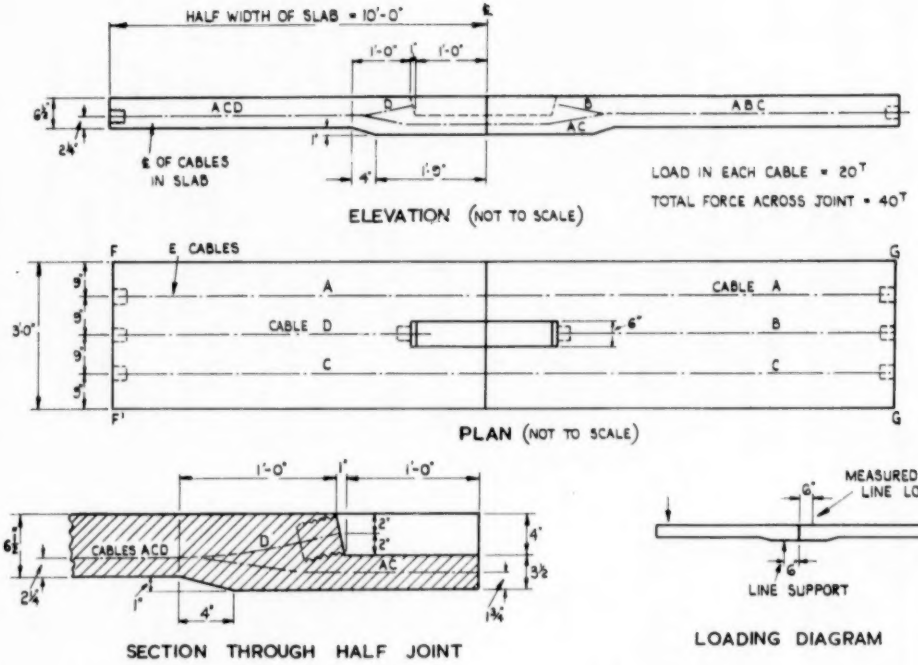

HALF WIDTH OF SLAB = 10'-0"
1'-0"
1'-0"
ACD
D
B
ABC
AC
6½"
24"
1"
℄ OF CABLES IN SLAB
4"
1'-0"
LOAD IN EACH CABLE = 20T
TOTAL FORCE ACROSS JOINT = 40T
ELEVATION (NOT TO SCALE)
F
E CABLES
G
A
CABLE A
CABLE D
6"
B
C
C
3'-0"
9"
9"
9"
9"
F'
G
PLAN (NOT TO SCALE)
1'-0"
1"
1'-0"
6½"
CABLES ACD
D
2"
2"
AC
4"
3½"
24"
1"
4"
1¾"
SECTION THROUGH HALF JOINT
MEASURED SHEAR LINE LOAD
6"
6"
LINE SUPPORT
LOADING DIAGRAM

FIG.17

100-ton aircraft covers an area with a 20-ft. periphery, the maximum shear per ft. run (much the same for a group of wheels as for an individual wheel) is only 2-1/2 tons. It is clear therefore that in a prestressed concrete carpet the necessary shear strength is easily provided and therefore the design will be governed by the strength required in bending.

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AIRPORT APPROACH, RUNWAY AND TAXIWAY LIGHTING SYSTEMS

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(Proc. Paper 1659)

SYNOPSIS

Many different airport lighting systems to aid the approach and landing of aircraft have been and still are in use. Much of the information about them has never been assembled into one publication. This paper briefly describes the various systems of approach, threshold, runway and taxiway lights. It also attempts to evaluate them by means of a set of design criteria developed from a series of principles of guidance needed by an aircraft pilot.

INTRODUCTION

Airport lighting systems are not usually designed in detail by the civil engineer. However, he is generally the technical man in overall charge of the design and review of plans for an airport, thus it would seem important that he have at least a general knowledge of the principles and purposes of the lighting systems which may be proposed and the guidance which each system should provide. This would appear to be especially timely now (December 1957) with several important new advances in airport lighting systems being developed and about to undergo field testing. The authors have attempted to collect and organize a wide diversity of source material on this subject; to their knowledge this has not been done before. While some of the systems described are obsolete they are included as a historical record which does much to explain the current status of airport lighting.

Airport lighting may include one or more of the following:

1. Obstruction lighting

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2. Airport beacons
3. Illuminated wind cones or wind tees
4. Ceiling light projectors
5. Approach lighting
6. Runway-threshold lighting
7. Runway lighting
8. Taxiway lighting
9. Lighted guidance signs
10. Apron floodlighting
11. Hangar lighting
12. Traffic control guidance

Lighting for most of these uses has been perfected and standardized for at least a decade; however, the following visual guidance systems are still undergoing development:

1. Approach lighting
2. Runway-threshold lighting
3. Runway lighting
4. Taxiway lighting

Pilots complain that their lighting is frequently inadequate and unsafe and particularly that many of the approach lighting configurations do not provide proper landing guidance.(38,47,51) In addition, they protest the many different and often outdated schemes currently in operation even at some of our largest airports. For example, until a few months ago a routine flight between Washington and Boston, stopping in Baltimore and New York, would encounter four different approach-lighting configurations.(4) As late as 1955 three different approach schemes were in use at the three largest airports in the New York City area.(51)

Since the earliest days of aviation, pilots have used landmarks and other visible objects for navigation. Electronic devices may supplant the pilot's eyes when flying at altitude, and the instrument landing system (ILS) and the ground controlled approach system (GCA) have helped make landing operations safer especially under low visibility conditions or at night, as they show the pilot where and at what rate to begin his landing descent. Electronic aids begin to lose accuracy, however, between 150 and 250 feet above the ground, and so the final phase of approach and landing must be carried out using visual means alone.(29,4) Visual aids become the necessary bridge for the pilot from air to ground, helping him to properly orient and guide his plane to a safe landing while moving at speeds of up to 150 miles per hour.(29,37)

The pilot's problems in approach and landing must be understood and the elements of guidance used by him in good visibility must be artificially duplicated in poor visual conditions if a successful visual aid is to be designed. Therefore, the basic principles involved in landing an aircraft in good and poor visibility must be examined before the operation of the various approach lighting systems can be described.

Theory of Airplane Landing

An airplane while landing can be thought of as a moving coordinate system,

the airplane, approaching a stationary coordinate system, the runway,* with the two being brought into alignment as they merge. When it has descended to an altitude of 150 to 300 feet the airplane should be located several thousand feet from the runway end; then the final landing approach may begin.(29) Fig. 1 shows the coordinate system of an airplane as it approaches the runway coordinate system. In addition to movement along any of three axes an airplane is also free to rotate about them. To land it is necessary to rotate, orient and translate the coordinate system of the airplane to coincide with the coordinate system of the runway. During good daytime visibility three dimensional objects on the ground provide the needed reference to the runway coordinate system. In low visibility conditions and at night artificial means of visual guidance must be provided, and will be most successful if duplicating the guidance elements afforded by three-dimensional objects. The problems inherent in these operations will be discussed separately for each of the three major visibility conditions.

Landings With Good Daytime Visibility

With good daytime visibility, a multitude of landmarks can be seen, such as trees, runways, buildings and towers. These objects provide visual perspective which affords optimum guidance to aid the pilot in landing.

Airport Identification

Under good visual conditions the airport and its runways are readily identified and a pilot usually needs to make only small corrections to his approach path.(29)

Correcting the Approach Path

The elements of guidance provided by three-dimensional objects are seldom analyzed by the average person in his everyday movements,(17) but in moving from one place to another he is moving his coordinate system in relation to fixed ground coordinates. This guidance is somewhat similar to that needed by pilots when landing; they too make automatic adjustments without separating the guidance afforded into its component parts.(4,14) Examining these components of guidance will be helpful as a basis for understanding the guidance needed by a pilot when normal three-dimensional objects are invisible.

Alignment Guidance.—A pilot must know if his airplane is headed straight towards the runway.

A driver on a straight highway almost subconsciously steers his moving car in relation to the three-dimensional view of the road stretching out before him. However, his predominant guidance comes from the direction coordinate of the road; this is intensified by the road edges and the painted centerline.

Just as a driver aligns his car with direction elements on the highway, the flyer can line up his airplane from the perspective guidance offered by the runway. The coordinate parallel to the runway centerline provides a pilot with such directional alignment.

Roll Guidance.—A pilot must know if his airplane is banked in relation to the surface of the ground; this is spoken of as aircraft roll or attitude. If such a condition were uncorrected the low wing would strike the runway.

*The usual angle of approach or glide path is $2\text{-}1/2^{\circ}$, though approaches are sometimes made at angles of 4 to 6 degrees.(29)

If one wishes to judge by eye whether a picture is level, he usually compares the top or bottom of the frame with such things as a table top or the horizontal line formed by the intersection of a wall and ceiling. In the same manner, one may judge that a pencil held up is truly vertical by comparing it with known vertical elements such as a table leg or book case side. Both of these judgments are comparisons of parallelism. One can estimate the degree of parallelism of any two lines quite accurately* when they are viewed perpendicularly to the line of sight.

In a similar manner a pilot can judge whether his aircraft is banked by observing the total three-dimensional picture, but especially by noting that the horizon and other horizontal elements on the ground are tilted (not parallel) with respect to horizontal lines in the airplane.

Height and Distance Guidance.—A pilot can successfully merge his moving coordinate system and the fixed ground coordinate system only if he has adequate height and distance guidance. This information tells him at any time how far he is from the runway, and how high the airplane is above the ground.

One estimates the magnitude of a given distance or height by the relative sizes of known or familiar objects; this is a learned process developed with experience.

Distance judgments are made from the complete three-dimensional picture one sees; the components which contribute most to these evaluations are vertical and horizontal elements. At distances of several hundred feet, vertical components are often more distinctive than horizontal ones.

One best judges heights by reference to familiar vertical elements or surfaces.(17,21) A demonstration of this is provided by looking out of a third or fourth floor window and seeing that objects such as cars or poles (which contain vertical components) provide the best clue as to height, being aided perhaps by familiar objects in the plane of the ground. This perspective view of buildings, trees, or towers aids the pilot in correctly judging his height and distance from the runway threshold.(49)

Landings With Good Nighttime Visibility

At night, landmarks and ground references are invisible. Therefore, some system of lights must be used to provide visual guidance.

Airport Identification

At night a rotating beacon identifies the airport for approaching planes. Flashing alternate white and green beams help the pilot distinguish the airport from other lights in the area.(7,9) In addition, obstructions must be lighted so that a pilot may identify and avoid them. Lights showing aviation red are used for this, their arrangement having been standardized in the United States and most of the world.(12)

Correcting the Approach Path

A pilot landing at night with good visibility conditions requires the same information needed in the daytime. In the absence of any system of lights, a

*In the special case of vertical or horizontal estimates we are aided by a retinal coordinate system. This coordinate system of the eye has developed partly by learning from past judgment and partly from an awareness of the line of action of gravitational effects.(39) However, in the absence of visual guidance, judgments of the truly vertical and the truly horizontal may be in error by as much as 6 to 10 degrees.(40)

faintly visible horizon would be the only ground guidance a pilot could see.

Lighting along the sides of the runway shows the pilot where to land and also provides him with alignment guidance. Height and distance information may be inferred by the apparent spacing and angular relationships of the parallel rows of runway lights. If some form of lighting is extended from the runway into the approach area this directional guidance is further improved. In addition, with some approach-lighting systems, roll, height, and distance judgments may be significantly aided.* These lights do not attempt to provide illumination of the approach and runway areas; their function is to serve as informative markers; they act as signal lights.

Poor Visibility Landings

Poor visual conditions may occur either in the daytime or at night. With poor daytime visibility the

> "Picture seen by the pilot as the ground first looms up out of the fog has a good deal of. . .unreality, and some of the pilot's difficulties undoubtedly spring from this. This unreality is partly due to the absence of colours and shadows, and partly to the absence of solid objects of known size, particularly objects with known dimensions transverse to the centre of the runway."(4)

Visual guidance for day and night poor visibility conditions is provided by high-intensity lighting systems. In addition to simulating the guidance available with good visibility, these lighting systems must also incorporate features peculiar to low visual conditions. The basic relationships of aircraft approach speed, time, and distance will affect their design, as will the factors of ceiling, visual range and critical height.

Landing Speed

Landings must be made somewhat above the stalling speed of the aircraft; the CAA requiring 1.3 times the stalling speed for all approaches. For modern planes such as the Constellation 1049C, 130 miles per hour (191 feet per second) is the minimum allowed; it may vary between 120 and 160 miles per hour for other large planes.(3)

Time Relationships in Landing

The distance from which lights may be seen is lessened when visibility is low, reducing the time available for making corrections to the flight path once they do become visible. Fig. 2 shows the time, height, and distance relationships for low ceiling approaches.**

Breaking through a 200-foot ceiling at 150 miles per hour while on the glide path an airplane is only 3580 feet (16 seconds) from the runway end. Since an aircraft should be "straightened away" for a landing at least 2000 feet (nine seconds) from the runway, the pilot has only 1580 feet or 7 seconds to make any changes in his heading.(29)

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* In the United States at present approach-lighting systems are only used on runways equipped with electronic landing systems (ILS or GCA). Current European practice is to use approach lights for non-instrument runways as well.

**In aeronautics, ceiling refers to the height of the bottom of a cloud layer.

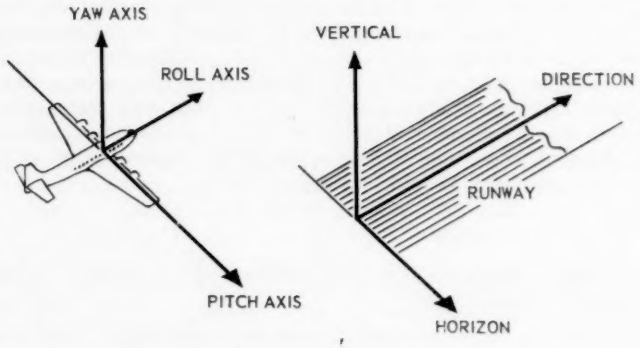

FIGURE 1-RUNWAY AND AIRPLANE COORDINATE SYSTEMS

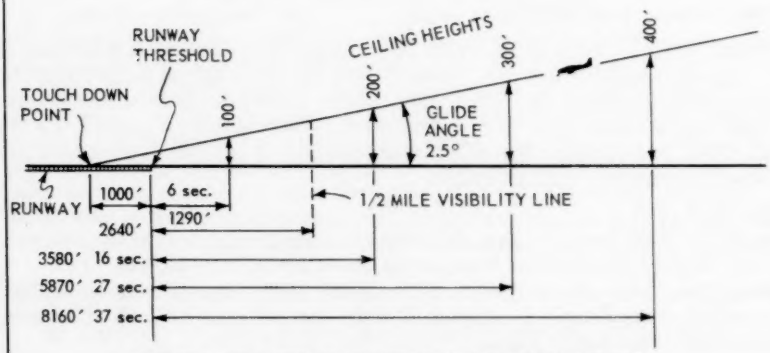

FIGURE 2-TIME, HEIGHT AND DISTANCE RELATIONSHIPS FOR LOW CEILING APPROACHES. BASIS: 150 mph=220 ft./sec.

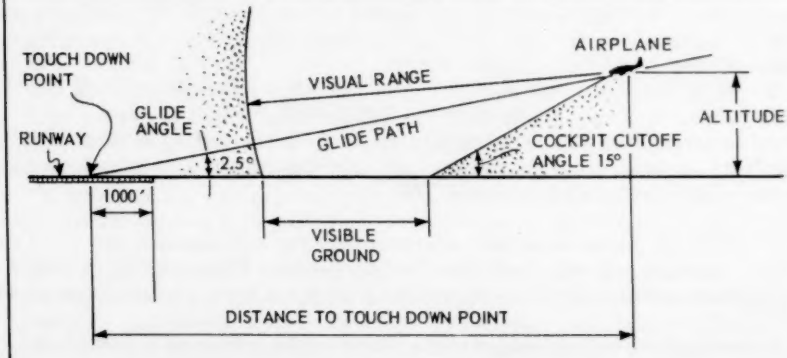

FIGURE 3-RELATIONSHIP OF VISUAL RANGE TO GROUND VISIBILITY

Thus the ceiling height directly determines the pilot's exposure time to visible aids. It has been found through experience that three seconds is the normal minimum reaction time for a pilot to both see a visual aid and cause the airplane to react as a result.

> "This type of reaction should be further explained as the time required for analysis and appraisal of the corrective action required, the time to apply the control movements required, the time for the aircraft to respond and the time to observe that the corrective force of action is taking place . . ."(36)

Visual Range and Ceiling

Visual range is the distance a pilot can see a visual aid through a given atmospheric condition such as haze, fog, smoke, et cetera.(29) It is shown in Fig. 3 as a limiting slant distance when spoken of in relation to landing approaches. In conjunction with the visual cutoff caused by the construction of the cockpit, it directly determines the length of ground visible to the pilot.(4)

Ceiling is the vertical distance from the ground to the underside of a cloud layer overhead.

The visual range decreases with increasing thickness of haze or fog. An unlimited visual range can exist below a low ceiling. Conversely with a high ceiling it is possible to have a haze limiting the visual range.

The CAA has used the concepts of visual range and ceiling to set operating limits below which aircraft must adhere to special regulations governing flying and the use of electronic aids for landing. When landing, electronic aids are not needed if the ceiling is 1000 feet or higher, and the visual range is three miles or greater. These conditions form the minimum requirements for which visual flight rules (VFR) are applicable.(11)

When the ceiling and visual range are below VFR conditions CAA regulations require pilots to land under instrument flight rules (IFR), calling for the use of electronic aids when landing. Minimum ceilings and visual ranges for IFR conditions have been imposed for all civil airports in the United States. The minima vary from airport to airport with the lowest authorized being a 200-foot ceiling with 1/2 mile visibility, such as at Pittsburgh.(11)

At present the determination of these minimums is based on meteorological (MET) visibilities. It is also possible to determine operating minimums based on Runway Visibility Range (RVR). MET visibilities are not necessarily indicative of the actual operating conditions encountered by a pilot, whereas RVR is a factual measurement of the distance a pilot can see the runway lights. Some European operations are now being authorized and conducted at RVR's of 900 feet; the CAA and Weather Bureau are currently experimenting with RVR at Newark Airport.(10)

Critical Height

As a plane using instrument guidance descends on the glide path, it reaches a height above ground where the pilot must switch from instrument to visual guidance. If the pilot then finds his visual guidance is inadequate or his position with respect to the runway is incorrect, he must have time to check his descent and "pull up." Due to reaction time and airplane response time the plane may sink as much as 100 feet before beginning to climb. Thus it becomes necessary to set a critical height above ground at which the pilot must initiate a pull out; this is usually 200 feet.(3)

Minimum Visual Range Required

A minimum of three seconds is needed to appraise the ground and then correct the airplane's position; if the approach speed is 150 miles per hour (220 feet per second) then in three seconds the plane will have traveled 660 feet. The range a pilot can see should at least equal the distance traversed while corrective action is taking place; otherwise he cannot see where his corrective actions are taking him. Thus for aircraft of this speed a 660-foot distance is the minimum visual range necessary for successful landings (Fig. 4).(36)

Location of Visual Aids

When a plane on the glide path is at a 200-foot critical height, a visual range of 3585 feet is necessary to see the runway.(29) Fig. 4 shows that for an airplane at this critical height with a speed calling for a minimum visual range of 660 feet an approach lighting aid must extend 3000 feet beyond the threshold to be of any use.(4)

Identification of Approach Lights

Rapid identification of approach lights is of paramount importance as the transition from instruments to visual flight must be accomplished as speedily as possible. If the approach light system does not have high fog-penetrating capabilities or if it is not readily distinguishable from other lights in the area a pilot must pull up and try again. These missed approaches lessen the landing capacity of an airport and are costly in both time and money for an airline.(50) At a busy terminal under IFR conditions aircraft landings may be spaced at two-minute intervals to allow a safety factor in operations. Every missed approach takes the same amount of time as a successful one. Thus, six missed approaches per hour would mean a twenty per cent reduction in the runway acceptance rate.

Correcting the Approach Path

In addition to ready identification of the approach lights, pilots flying in poor visual conditions also require adequate roll, alignment, height and distance guidance to merge their moving coordinate system with that of the ground.(29)

Displacement Guidance.—With good visibility conditions a pilot can easily judge that he is flying correctly along the runway centerline rather than parallel to the centerline but displaced to one side of it. Under low visibility conditions with approach-light systems containing only direction elements a pilot is unable to tell if his plane is laterally displaced or if it is banked. Figs. 6 and 7 show the pilot's perspective view for each of these cases; he cannot tell instantly what corrective actions are necessary. Introduction of a second visible coordinate would be necessary to provide the needed guidance.(29)

Time and Visual Range Factors.—With the probability of only a small portion of the approach-lighting system being visible, and the need for quick decisive action by the pilot to correct errors of alignment, roll, height and distance, the time and visual range factors previously discussed must be considered when applying the elements of guidance to the development of an actual approach lighting system. This means that systems should give continuous or repetitive indications of guidance to the pilot, and present this information in such a simple manner that it can be acted upon almost from intuition. Any systems which fail in these respects may contribute to missed approaches or crashes.(4,29)

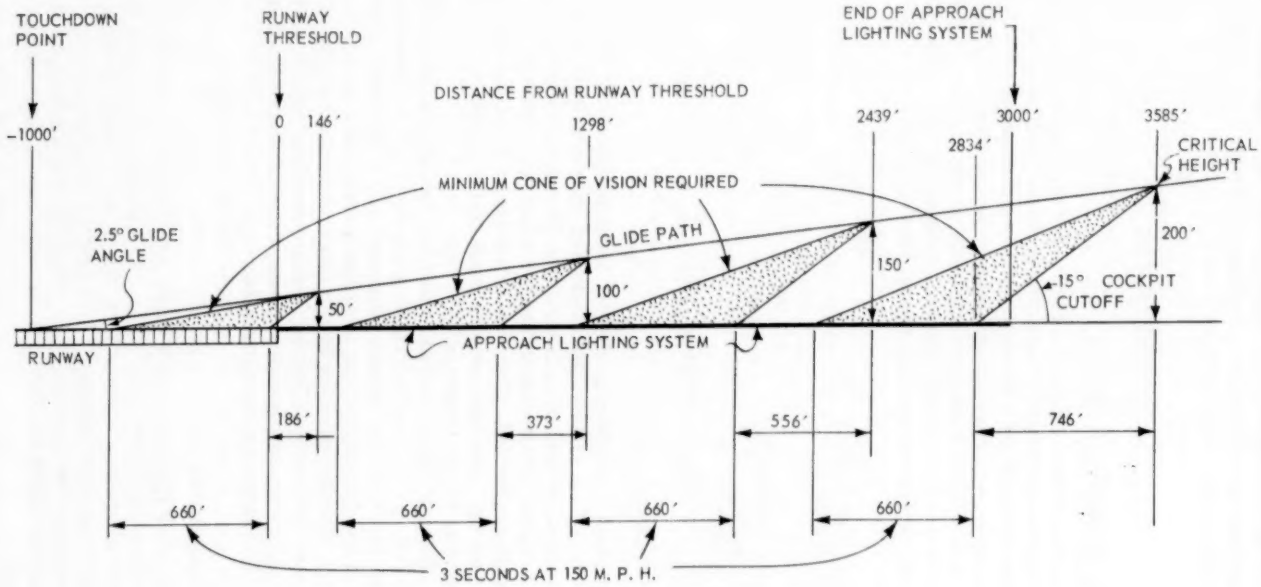

FIGURE 4–RELATIONSHIPS OF VISUAL RANGE, ALTITUDE, DISTANCE FROM RUNWAY AND THE APPROACH LIGHTING SYSTEM.

If these distance and time relationships which must exist when an airplane is landing in low visibility or at night are kept in mind, it becomes easier to appraise the various approach lighting systems that have been or still are in use or are being proposed for adoption.

Approach Lighting

Design Criteria for Approach Lighting

As we have seen, when good night visibility prevails approach lights are a desirable supplement to a runway-lighting system as an aid to pilots in landing, but approach-time effects would not enter into the design. At times of reduced visibility, however, approach lights serve as the only visual approach aid available. These lights must provide proper guidance during the few seconds it takes to travel from the approach area to the runway threshold. Therefore, approach lights must be designed for this critical condition, and should provide:

1. Immediate identification
2. Alignment guidance
3. Roll guidance
4. Displacement guidance
5. Height guidance
6. Distance guidance
7. Simplicity of interpretation and guidance

Implementation of Design Criteria

Approach lighting has evolved gradually; early designers apparently had little conception of all the criteria just presented and proceeded on an empirical basis. Only repeated landing failures led to the realization that current designs did not provide sufficient guidance, and that further insight into pilot guidance problems was needed. Unfortunately many of these obsolete systems are still in use bearing mute testimony to many heated fights over proper application of correct design criteria.

It is only since World War II that scientifically designed approach systems have been employed. So-called theoretical designs, practical schemes, and rational methods have been continually proposed until today there are eleven major systems in use (see discussion to follow) as well as a multitude of hybrid special ones. These conditions though now chaotic should rapidly improve as a result of recent advances in lighting, international agreement on the design of approach systems, and greatly increased availability of funds for approach lighting installation and modernization.

Approach Lighting Systems

The authors believe that approach lighting may best be classified as utilizing one, two or three coordinates for guidance. Because of collision danger in approach zones when using vertical projections most approach-light systems are restricted to the surface of the ground, and thus provide only one or two of the necessary coordinates. This requires that the pilot must consciously interpret height and distance, and this may in turn lead to incorrect judgments.

Single-Coordinate Systems

The earliest approach lighting was a single row of lights leading from the approach area to the runway threshold. During World War II, double and multi-row systems were tried, but they still provided only one guidance coordinate. Single-coordinate systems are now obsolete, but they are still used at many airports in the United States and elsewhere.

Single-Axial Row System.—Fig. 5 shows the single-axial-row system, using lights placed 100 feet apart on the extension of the runway centerline. They indicate direction to the runway, but "the pilot's only indication as to his altitude is a small variation in the visual angle subtended by successive pairs of lights."(60) When the horizon can be seen it provides adequate roll guidance since it acts as a second coordinate. When it is obscured because of low visibility a pilot is unable to tell if his plane is laterally displaced or banked. Fig. 6 shows a perspective view of the single-row system with the airplane displaced 60 per cent of the height. Fig. 7 shows a pilot's perspective view of the system when the airplane is banked 30°. If the horizon is obscured, both become identical and the pilot cannot be certain what corrective maneuvers are are necessary for landing.(29)

The single-axial-row is the simplest type of approach system, but systems offering greater guidance have made it obsolete. There is one neon-center-row system still in use in the United States.(51)

Left-Hand-Row System.—Another one-coordinate system, the left-hand-row, has a single line of lights as in the axial row system but they are placed along the extension of the left edge of the runway. This scheme has the same deficiencies noted for the axial-row grouping, with the added difficulty of determining the location of the center of the runway. A five man civil and military committee reported: "The left hand row has the greatest amount of erroneous information. It is easy to see, but to extract runway centerline information is often difficult and erroneous."(45)

The left-hand-row is still in operation at La Guardia airport, where the installation comprises both neon and high-intensity lighting units.(47) The United States adopted the left-hand-row as its standard several years before World War II. Although long since obsolete and now undergoing conversion to Configuration "A" systems under the Federal Airway Plan 1957-1962 as rapidly as funds will permit, the scheme is still currently used at several dozen American airports.(28,51)

Double-Row System.—Double-row systems are also single-coordinate schemes (Fig. 8). The individual lines are one dimensional, and even when combined retain the one-dimensional character of the separate lines. However, if the distance between rows is standardized, it is possible to gage airplane height from the angle formed by perspective convergence. Fig. 9 shows this relationship between angle and height. As in single-row systems, guidance is seriously impaired if the horizon is not visible, and similar ambiguity between bank and alignment will be present. In addition if only one row is visible due to weather conditions pilots do not know which one they are looking at.(38) This may be corrected by the use of different colored lights to distinguish rows. "Parallel or converging approach-light systems are difficult to deal with since basically they may cause pilots to mistake the rows for runway lights and land between them. There have been several occasions when pilots have either landed or nearly landed between multiple rows of approach lights."(30)

During World War II, both the Air Corps and the Navy used the double-row system, which was considered an advance over single-row systems. The

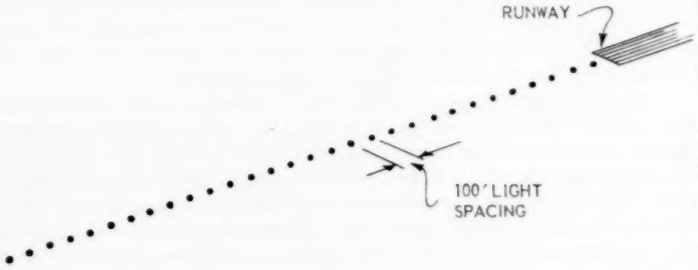

FIGURE 5-SINGLE LINE APPROACH LIGHT SYSTEM

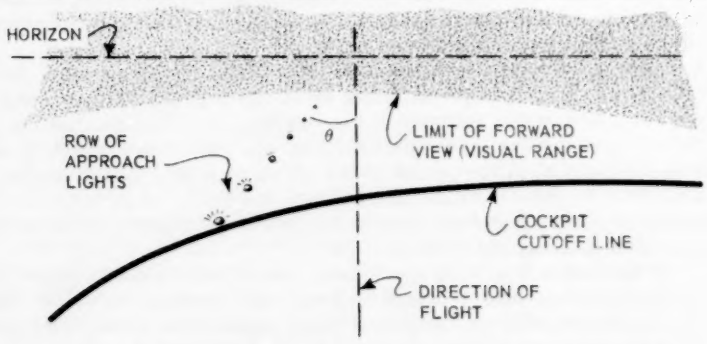

FIGURE 6–VIEW IN LOW VISIBILITY CONDITIONS SEEN BY PILOT OVER SINGLE LINE APPROACH LIGHT SYSTEM WHEN THE AIRCRAFT IS DISPLACED LATERALLY BUT NOT BANKED.

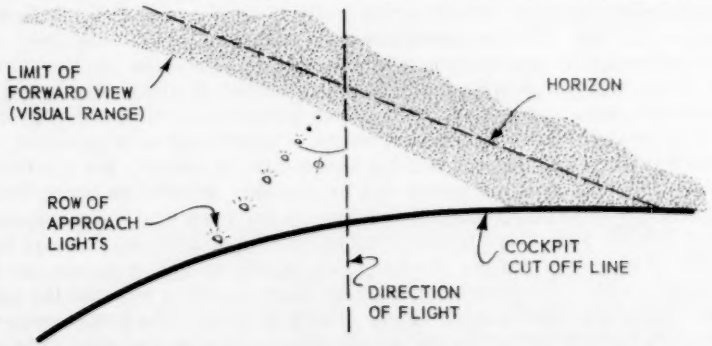

FIGURE 7–VIEW IN LOW VISIBILITY CONDITIONS SEEN BY PILOT OVER SINGLE LINE APPROACH LIGHT SYSTEM WHEN THE AIRCRAFT IS CORRECTLY ALIGNED AND ALSO BANKED.

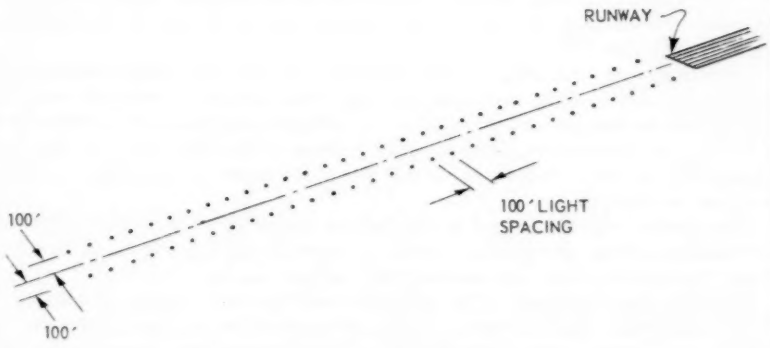

FIGURE 8–DOUBLE PARALLEL ROW APPROACH LIGHT SYSTEM

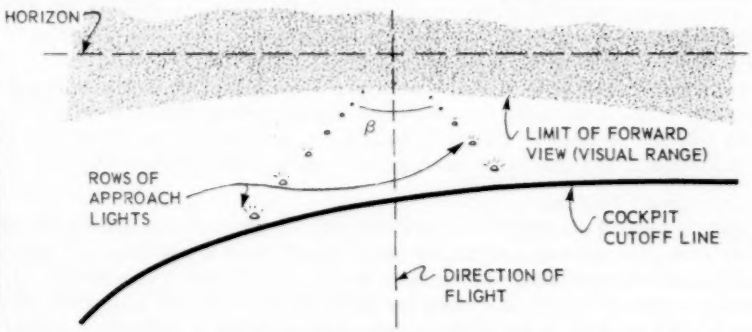

FIGURE 9–VIEW IN LOW VISIBILITY CONDITIONS SEEN BY PILOT OVER DOUBLE PARALLEL ROW APPROACH LIGHT SYSTEM WHEN AIRCRAFT IS CORRECTLY ALIGNED

$$\tan \beta/2 = \frac{\text{1/2 distance between parallel rows}}{\text{height of aircraft}}$$

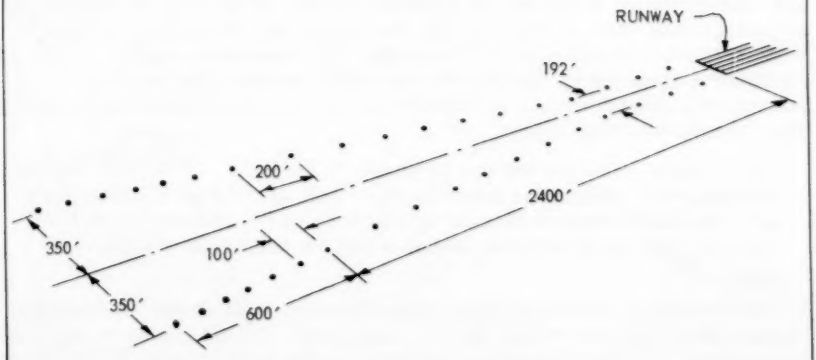

FIGURE 10–FUNNEL APPROACH LIGHT SYSTEM

authors believe this advantage may have been due to the double-row system being the first configuration to use high-intensity lighting units, which could be seen in low visibility from a greater distance than any lights till then developed. Though now outmoded, this system is still in use at 14 airports in the United States.(38)

Funnel System.—A slight variation of the double-row configuration is the funnel approach system shown in Fig. 10. This system is subject to the same operational problems as the double-row scheme with the added difficulty—due to wider row spacing—of discerning both rows under low visibility conditions.(38) If only one row is visible the orientation of the runway centerline becomes an enigma.

The system was developed by the United States Air Force and installed at seven bases during the Berlin Airlift. Extensive testing convinced the Air Force that this system was unsuited for further installations.(38)

Multiple-Row Systems.—The multiple-row system consists of four or more widely separated lines of lights; these are parallel to the extended runway centerline (see Fig. 11). It was believed that these extra lines would facilitate identification of the approach aid.(30,44) However, its operational difficulties are the same as those of double-row systems. Multi-row systems "may result in confusing the pilot as to which row is first sighted. Also, when drift conditions are present the guidance elements are very difficult to interpret."(30) These difficulties may be seen in Fig. 12.

The United States Navy tested a multiple-row system at Patuxent Naval Base about 1948, employing 158 lighting units spaced as shown in Fig. 11. The system was not adopted by the Navy because of the complicated nature of its light-placement, and confusion during low visibility conditions.(44)

Two-Coordinate Systems

Adding a second coordinate allows the pilot to correct roll errors by visual observation. The second coordinate takes the form of transverse elements modifying one-dimensional systems; these may take three basic forms: 1) transverse rows of lights, the rows (or bars) being 50 to 100 feet wide; 2) rows made of short bars (stub bars) of closely-spaced lights or tube-type lights such as neon; 3) combinations of one or more of the above.

Calvert System.—The limitations described in preceding systems led Mr. E. S. Calvert (of the Royal Aircraft Establishment) to develop the two coordinate approach system which bears his name (Fig. 13). Lights are spaced at 100-foot intervals on the extension of the runway centerline. In addition, there are transverse rows of lights at 500-foot intervals. Directional alignment with the runway is indicated by the centerline placement of lights. Roll guidance is provided by the transverse rows. Because this is a two-dimensional system errors of displacement may be determined and corrected. The crossbars always appear

> "To be parallel to the horizon as shown in Figures. . .(15,17,18) and this distinguishes one picture from the other just as the real horizon would do. The pilot's task is then the manageable one of manoeuvering the aircraft until the transverse element and the centerline make a right angle."(30)

The crossbars have been made proportional to their distances from the runway threshold thus aiding distance judgments. Height guidance requires experienced interpretation of the system's perspective picture.(60) Correct

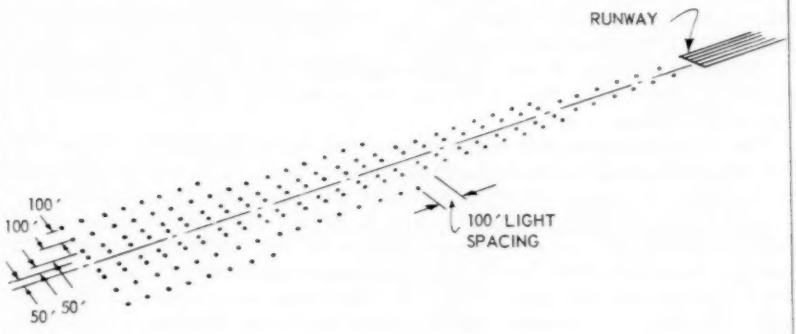

FIGURE 11–MULTI-LINE APPROACH LIGHT SYSTEM

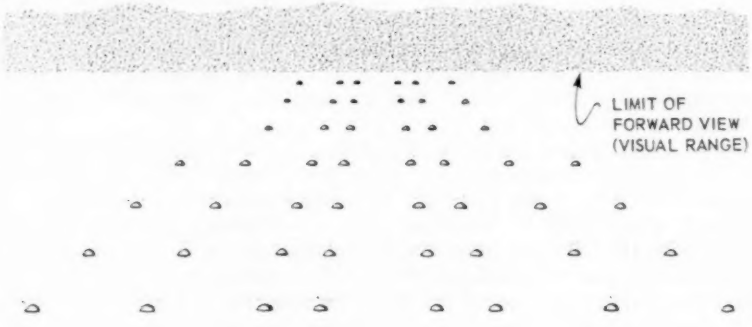

FIGURE 12–PERSPECTIVE VIEW OF MULTI-LINE APPROACH LIGHT SYSTEM

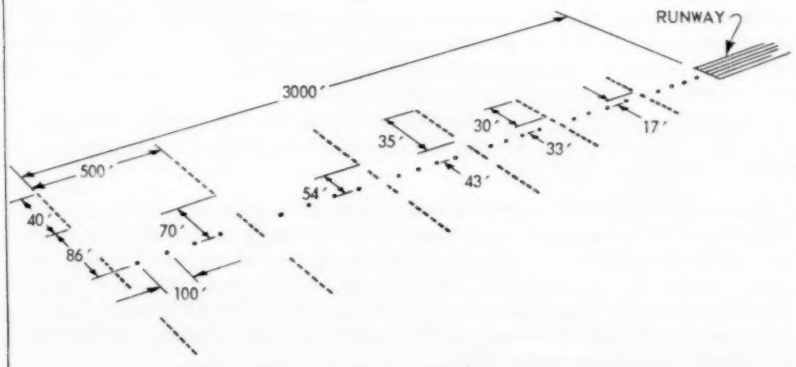

FIGURE 13–CALVERT BAR APPROACH LIGHT SYSTEM

approach paths, however, can be determined by noting the speed at which the crossbars appear to move down the airplane's windshield. If the angle of approach is too steep, the bars will stop this apparent movement, thus indicating that corrective action is necessary.(50)

Crossbar spacing is less than the minimum visual range required for low visibility guidance, so that it will always be possible to see at least one crossbar in the system.

The Calvert system has found widespread use in Europe and Japan.(42) The International Civil Aviation Organization (ICAO) has approved this system as satisfying its requirements for an approach-lighting configuration.

CAA Configuration "A" (ALPA-ATA System).—Many pilots believe the Calvert system provides too few crossbars for low visibility guidance. Consequently, the ALPA-ATA (Air Line Pilots Association-Air Transport Association) system was developed (Fig. 17). This lighting scheme is laid out for 3000 feet along the extended runway centerline using transverse bars placed at 100-foot intervals; lights used in these bars are closely spaced to give the effect of a continuous 14-foot bar of light.

Direction, roll and displacement guidance are provided by this two-coordinate system. Height judgments are aided by using standardized bar lengths throughout the approach path; an increase in apparent length of bars being related to decreased heights. A wide crossbar placed 1000 feet from the runway edge indicates the remaining distance to the runway threshold. However, this bar is obscured by cockpit cutoff once the airplane is 1400 feet or less from the runway threshold.(36)

"Under conditions of restricted visibility, there is no distance indication given until the pilot comes within sight of the crossbar, which is 1000 feet from the threshold. From this point on to the runway, the indication of distance is adequate."(61) Some experts doubt whether the 14-foot transverse bars are long enough to provide adequate roll guidance,(35,61) though many others feel that they are. Configuration "A" is supported by ALPA, ATA, ICAO, and in addition is one of the three systems the CAA and the Air Coordinating Committee ACC have currently standardized for American airports. This approach scheme is authorized for all civil airports not jointly used by civil and military aircraft, and obsolete systems are slowly being changed to meet the new standards. As of November 1957 ". . . there are 17 configuration "A" systems now in operation in the United States and 14 under construction. In addition to these, 52 new systems are now programmed for installation. Of these 52 systems 37 will be modifications or conversions of existing systems. There will remain 35 existing systems to be changed as rapidly as funds will permit."(28) This system is also used in Spain.(1)

CAA Configuration "B."—In the United States, the Air Force does not permit obstructions of any kind in the last 1000 feet before the runway threshold.(56) They feel that

> "Approach lights must not constitute a hazard to aircraft which may undershoot or overshoot (the runway). As a result of statistical studies on all AF accidents, . . . AF Flight Safety personnel apparently believe that cleared overun areas. . . are more important than good approach lighting systems. This attitude . . . now prevents the AF from adopting the unmodified centerline system (the CAA system A) advocated by the Airline Pilots Association."(38)

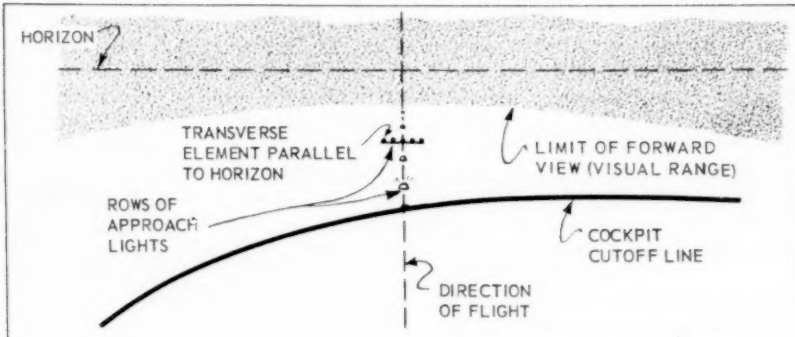

FIGURE 14–VIEW IN LOW VISIBILITY CONDITIONS SEEN BY PILOT OVER TWO-COORDINATE APPROACH LIGHT SYSTEM WHEN AIRCRAFT IS STRADDLING THE LIGHTS AND UNBANKED

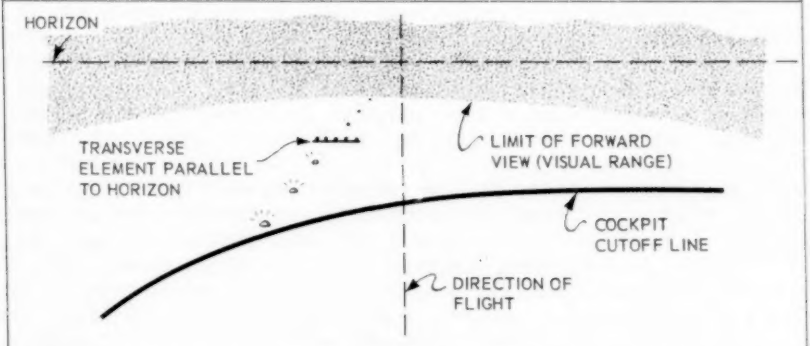

FIGURE 15–VIEW IN LOW VISIBILITY CONDITIONSSEEN BY PILOT OVER TWO-COORDINATE APPROACH LIGHT SYSTEM WHEN AIRCRAFT IS DISPLACED LATERALLY BUT NOT BANKED

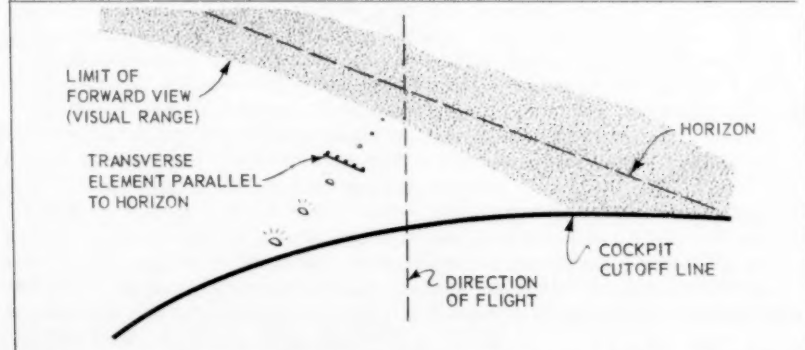

FIGURE 16–VIEW IN LOW VISIBILITY CONDITIONS SEEN BY PILOT OVER TWO-COODINATE APPROACH LIGHT SYSTEM WHEN THE AIRCRAFT IS CORRECTLY ALIGNED AND ALSO BANKED

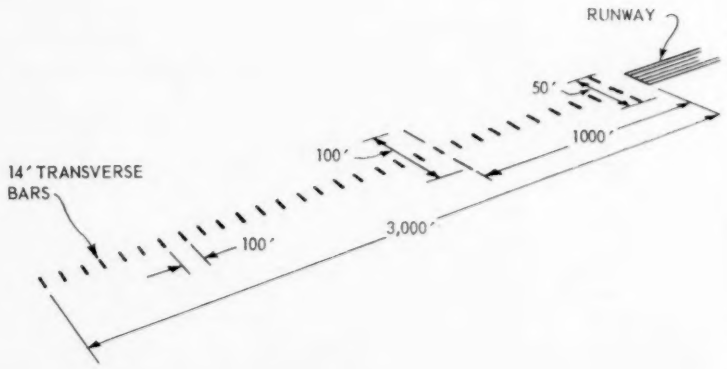

FIGURE 17–CONFIGURATION "A" APPROACH LIGHT SYSTEM

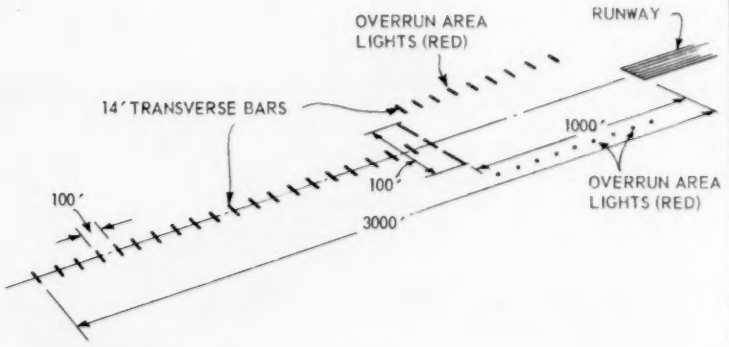

FIGURE 18–CONFIGURATION "B" (U. S. AIR FORCE) APPROACH LIGHT SYSTEM

Consequently, any system using raised lights in this area would be unacceptable. Configuration "B", Fig. 18, was developed as a solution; it and Configuration "A" are similar except for their treatment of the last 1000 feet. In this overrun area, the centerline bars are replaced by rows of lights near the extended runway edges, the left rows being 14-foot transverse bars for roll guidance. Red filters prevent confusion with runway lighting warning the pilot not to land here.

The Air Force states: "Approach Lighting Systems must . . . provide guidance for fighter aircraft which may have severe cockpit visibility limitations. A pure centerline system is completely unsatisfactory for low visibility approaches . . ."(38) Side guidance is provided for these fighter planes by Configuration "B".

The CAA requires that Configuration "B" be installed at all airports jointly used by civil and military aircraft. Civil pilots, however, protest the lack of centerline guidance in the overrun portion of this scheme. Therefore, the Air Force has permitted a few installations of Configuration "A" at joint-use fields on an experimental basis using lamp housings mounted on frangible couplings in the unpaved overrun area.(28)

System B installations have been made at five United States airports. These include Pittsburgh.(47) A shortened version was completed at Boston's Logan International Airport in December 1956.(18)

Configuration "A" Modified with Flush Lighting.—An experimental installation the results of which give promise of settling the controversy between proponents of Configuration "A" and Configuration "B" and developing as a single National Standard was tested at March Air Force Base, California, in the spring of 1957. Systems tested were a Configuration "A" with addition of transverse roll guidance bars and extended edge lighting arranged so various parts could be tried separately. The 1000 feet of 14-foot centerline lighting bars within the underrun area were installed in grid units flush with the ground, the so-called Elfaka light developed in the Netherlands.(53) These units are said to be sufficiently strong to withstand a direct landing by a 200 ton bomber without damage. The installation also incorporated in it a system of flashing stroboscopic lights discussed later. Visibility of the recessed units was excellent, even better than of the elevated conventional bars.(23) The report on the tests by both Air Force and Navy aircraft concluded that "test proved conclusively that centerline approach lighting is a basic requirement for an accepted national standard on approach lighting."(57)

The study also concluded that the rows of extended edge lighting and the transverse roll guidance bars tested were not a necessity but rather a luxury.

The Air Force thus seems to be modifying its previous insistance on side guidance and accepting a centerline crossbar approach system provided the last crossbars in the overrun area are in flush mounted units. Additional similar installations are now being programmed.

U.S.S.R. System.—In the Soviet Union until recently a parallel arrangement of lights on each side of the runway overrun area was used, with a single row extending beyond it, and two long crossbars. More recently a modification of the Calvert system has been adopted, calling for three equally spaced long crossbars and a row of short crossbars instead of single lights between the first two long crossbars (Fig. 20).(52)

French System.—The system used in France consists of a left-hand row with two crossbars of different colors 1250 feet apart (Fig. 19). It is a two-coordinate system providing roll and alignment guidance. Height guidance is

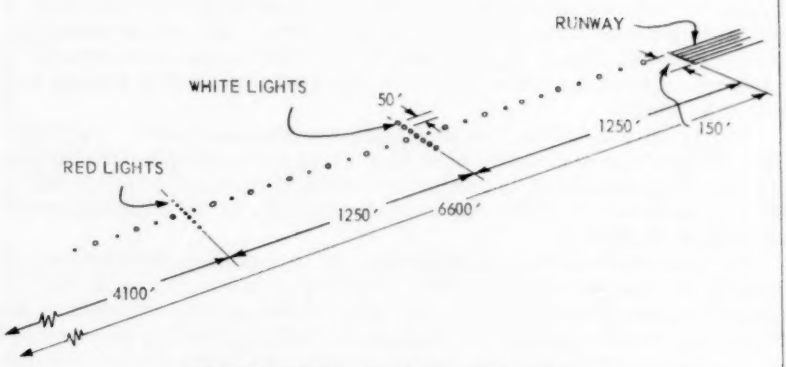

FIGURE 19–FRENCH APPROACH LIGHT SYSTEM

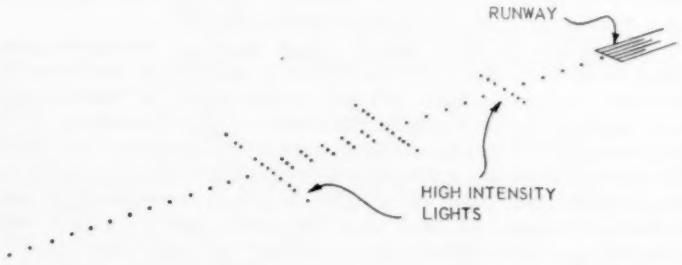

FIGURE 20–U. S. S. R. APPROACH LIGHT SYSTEM

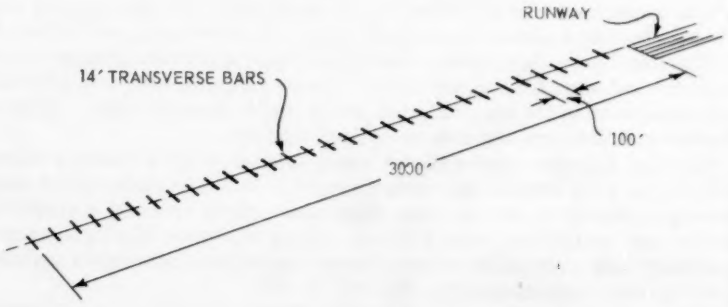

FIGURE 21–LEFT HAND BAR APPROACH LIGHT SYSTEM

the same as that provided by the Calvert system. Distance judgment is helped by the different coloring of the crossbars.

The French configuration was evaluated by civil and military pilots in a test at Patuxent River, Maryland. These pilots agreed with French pilots that the system has the inherent defects of all left-hand-row systems; i.e., information as to runway centerline location is difficult to extract. In addition, "perspective is difficult to interpret unless a large portion of the system can be seen."(45)

The French government is now replacing this system with one similar to the Calvert or Configuration "A" schemes.

Left-Hand-Bar System.—The left-hand-bar system consists essentially of 14-foot bars located along the extension of the left hand side of the runway (Fig. 21). Placed at 100-foot intervals, each bar is transverse to the direction of flight. This system resembles a Configuration "A" system which has been displaced from its centerline position to the left side of the runway and has had its wide 1000-foot bar removed.

The roll and height guidance is similar to that of Configuration "A". The adequacy of this roll guidance is questionable, the 14-foot bars possibly being too short to be effective.(35,61) If the runway lights are obscured by poor visibility a pilot has no indication of how far he is from the runway threshold; thus the system does not provide adequate distance guidance. Directional guidance is provided to the left hand side of the runway rather than to the runway centerline, and a pilot must consciously displace his plane to the right of the lighting units.

Currently, there are 19 left-side-bar systems operating in the United States.(38) One of America's busiest terminals, Chicago Midway, used this lighting scheme,(47) and in 1951 a left-hand-bar system was installed at Baltimore's Friendship International Airport.(19)

Three-Coordinate Systems

Height and Distance judgments are possible with two-coordinate lighting schemes, however the number of undershoot acidents attest to there being inherent errors in such a system. A three-coordinate system can best provide needed height and distance guidance.(4,21,49)

This guidance can be presented in two ways with three-dimensional systems. First, the principle relating the glide-path angle to height and distance may be used (Glide-path angle equals $\tan^{-1}\frac{\text{height}}{\text{distance}}$). There are two configurations which use this relationship. Secondly, systems may be developed which incorporate vertical elements for height and distance guidance; no configurations of this type have yet been used except experimentally.

Slope-Line System.—Developed by the CAA, the slope-line system was the American standard between 1949 and 1953. Fig. 22 shows that this is a double-row approach system; each row being composed of bars set at a 45° angle to the ground surface. The design is such that the plane formed by the lights of one row intersects the plane of the other row along the ideal glide path. A pilot correctly aligned on the path will see the bars as two continuous lines of light leading to the runway. If displaced from the ideal path, individual bars become visible. In relation to each other, the bars appear to point the direction the pilot must take to regain the glide path. Fig. 23 shows perspective views of this system for the nine directions from which aircraft may approach the runway.

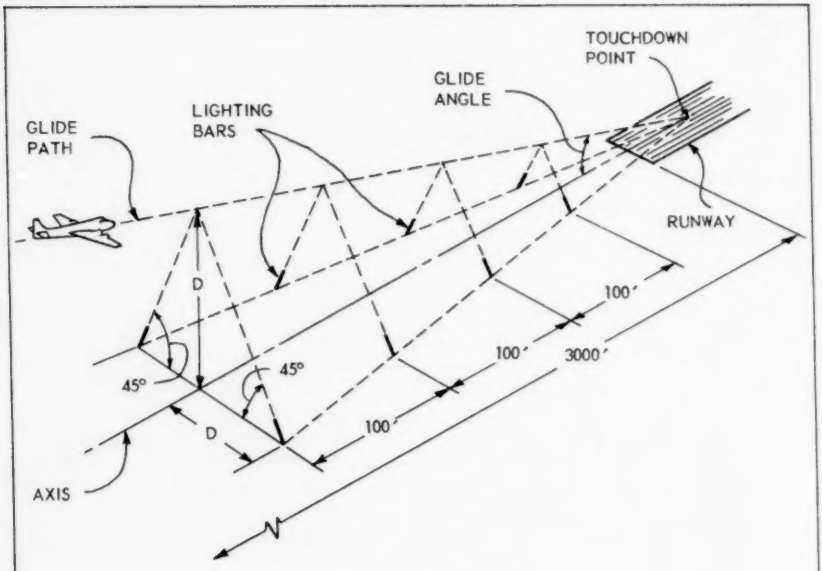

FIGURE 22–SLOPE LINE APPROACH LIGHT SYSTEM.

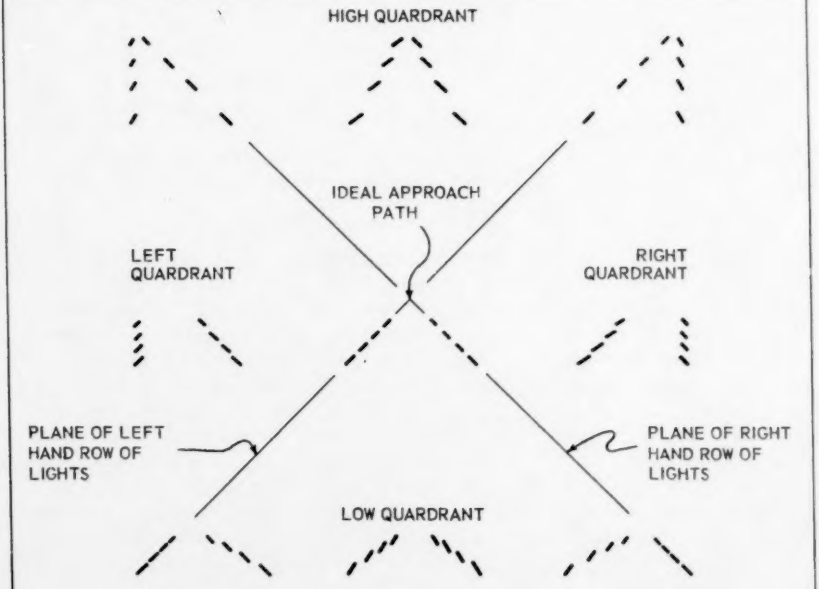

FIGURE 23–PERSPECTIVE VIEWS OF SLOPE LINE APPROACH LIGHT SYSTEM.

The slope-line system provides adequate alignment, roll, and displacement guidance by using the angular relation of glide path to height and distance. However, if not on the correct glide path a pilot must consciously interpret the visual directions offered by the system in order to correct his approach path. In poor visibility a pilot has only a few seconds to determine which one of nine possible views confronts him. If only one row is visible further confusion will result. This difficulty of interpretation does not satisfy the criteria of simplicity of interpretation and guidance.(45)

From an 18-month operational test of the slope-line and other systems, a five man civil and military committee reported:

> "While . . . (the slope-line system) provides the most complete information under good visibility conditions it is confusing and difficult to interpret under poor visibility. If only a few fixtures of one row are visible, the information is of little value in determining flight path correction or in confirming position and altitude."(45)

Experienced pilots point out that under certain atmospheric conditions, "slope line creates a 'mirage' effect which leads a pilot to believe he is too high and approaching nose-down."(59) At other times the runway appears to be tilting up.(59)

New York International Airport used the slope-line system until a recent crash destroyed the left side of the system. While the official report of the accident suggested pilot fatigue and an improper instrument approach as the cause, some pilots believe the Italian Airline plane which crashed there may have mistaken the approach system for runway lights and tried to land between the two rows.(24,44) This configuration has since been replaced by Configuration "A".(33) Currently, slope-line systems are in use at two airports,(59) Washington National and Los Angeles airport having recently been converted to Configuration "A".

Navy System (CAA Configuration "C").—The United States Navy has developed a scheme which combines the slope-line with other systems (Fig. 24). Because of its complicated layout, the system requires pilot-interpretation which makes it incompatible with the criteria of design simplicity. Configuration "C" ". . . is a confusing conglomeration of the Slopeline-Centerline, Calvert, and Funnel Systems."(38)

The only installation of this system has been at the Patuxent River Naval Air Station; the Navy endorses it despite the disapproval of the Air Force and the CAA.(51)

Three-Dimensional L System.—The use of vertical guidance elements in approach systems has been proposed by Dr. H. W. Rose (of the Air Force School of Aviation Medicine)(49) to provide accurate height and distance perception. Lighted markers in the shape of L's would be used in pairs one on each side of the approach and runway systems. The horizontal portion of each L would be transverse to the axis of the runway and the vertical segment would be located about 300 feet from the runway centerline. Both segments of the L would be of equal length; six to fourteen feet being recommended. Controlled size and lateral spacing and light-weight construction of the L's would minimize aircraft damage in the event of collision.

Fig. 25 shows these elements as they might appear in a modified Calvert system. The L's could also be used with Configuration "A". In the one test that has been conducted:*

*Kindley Air Force Base, Bermuda.

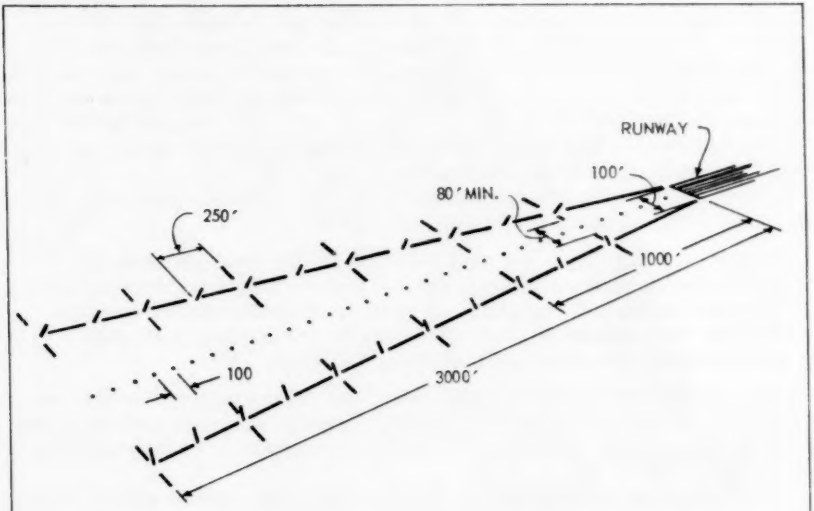

FIGURE 24–CONFIGURATION "C" (U. S. NAVY SYSTEM) APPROACH LIGHT SYSTEM.

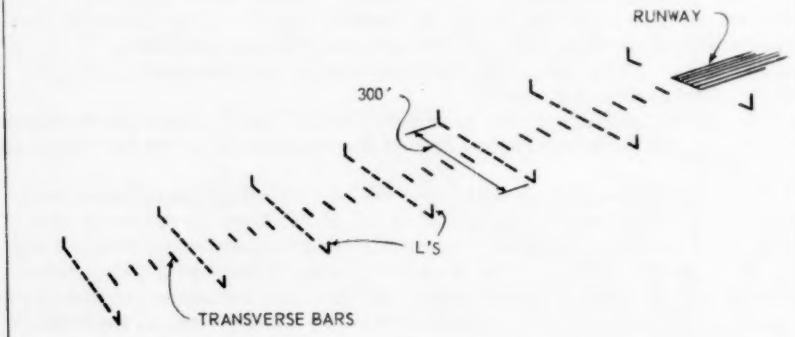

FIGURE 25–PROPOSED THREE-DIMENSIONAL L APPROACH LIGHT SYSTEM.

"Two of these visual aids (L's) were constructed and erected . . . They were tested at night and the crew comments indicated that the structures offer the necessary depth perception clues for spatial orientation during night landings."(21)

Further testing is needed, but this or similar systems may hold the key to final approach light perfection.

Auxiliary Aids for Visual Approach Guidance

Various auxiliary lighting aids may assist the use of the various approach lighting systems.

Flashing Condenser Discharge Lamps (EFAS)

Condenser discharge lamps are proving to be a very successful addition to approach-lighting systems.(54) They operate from a periodic discharge of energy stored in a capacitor, and produce a blue-white flash with a peak intensity of 30,000,000 candle power but of only five-thousandth of a second duration. When used with a Configuration "A" approach-lighting system they are placed directly below the 14-foot crossbars. In the March Air Force Base experimental installation they were located in a flush grid unit adjacent to the other lights making up the recessed crossbars. They are synchronized to discharge successively beginning with the unit furthest from the runway. A complete cycle is flashed twice each second, the "resulting effect . . . resembling a brilliant ball of light moving towards the runway at a speed of some 3600 miles per hour."(18) The intensity and effect of the flashes produce a pronounced attraction to the eye, providing immediate identification and lack of confusion with other lights.(15,54,23)

In operation, condenser discharge units are not needed except under conditions of poor visibility. Because of the very short duration of the flashes pilots are neither blinded nor lose their dark-adaption in spite of their intensity. However, some pilots believe that the condenser discharge lamps ". . . over-emphasized the directional guidance, and thereby eclipsed to some extent the value of the crossbars in providing roll guidance."(35)

These lighting units have been authorized by the CAA for use with Configuration "A" approach-lighting systems. In the United States they are already in use at Newark, New York International, Cleveland, Boston and Los Angeles Airports as well as at one military airport. Thirty-one of these systems have been ordered by CAA for installation at other airports. Two European airports are already equipped and one there and one in Canada are in process.(16.63)

Angle of Approach Indicators

Angle of approach indicators have been developed which indicate whether or not a pilot is on the correct glide path. The units usually show a yellow light to the pilot when flying too high, a red light when approaching too low, and a green light if the glide path is correct. Flashing the signal-beams prevents confusion with other lights surrounding the airport.

Student pilots of the United States Navy and Marine Corps tested such lights in the fall of 1952.

"Approximately one hundred night landings were made by students whose total night (flying) time was less than five hours . . . Their landings (using a glide path indicator) were consistently better than the same students

could make in daylight. . . This light was enthusiastically endorsed by all participants in this test. The only criticism came from the school authorities. They said we were making night landings so easy for this class of students that they would not be able to fly at night without this aid."(50)

ICAO recognizes the desirability of such lights but their use has been limited to experimental installations.(50) At Blackbush Airport in England angle of approach indicators were recently tested and "Almost without exception pilots found the . . . (indicators) of great value, both night and day."(33)

Several technical problems related to their construction and use have not been finally resolved. Moisture condensing on the filters caused some confusion between the colors; this should be capable of correction. There is still disagreement as to the best location of the indicators with respect to the runway; at Blackbush this was found to be along the runway edge 1000 feet from the threshold.(33)

Because these indicators must be located near the runway touchdown area they can be of use only during periods of good visibility, as an airplane operating with a minimum visual range of 660 feet would be over the runway before they came into view.

Threshold Lighting

While still airborne pilots must anticipate their actual touchdown. Runway lighting indicates the landing area but does not clearly delineate its beginning or threshold. Therefore, threshold lights are placed across each end of a runway. A pilot supplements them, except in fog, by using the landing lights of his airplane.(43)

Threshold Lighting Methods

The exact arrangement of threshold lighting varies with different design philosophies, the two criteria for such lighting being: 1) Identification of the threshold; 2) Simplicity of design.(37) By international agreement, the color emitted by all threshold lights is green.(31)

Method A*

Historically, method A was the first end-of-runway designation, with six lights placed in a line across the runway end (Fig. 26a).(8,31) While satisfying the simplicity criterion, it provides a minimum of threshold identification. Though generally considered insufficient, it is still used at many small airports.

Method B

Method B (Fig. 26b) uses two bars of green light at the threshold. These are located at right angles to the runway centerline, one end of each bar being 40 feet from the centerline and the other end in line with the runway edge lighting. Thus, the length of bars will vary with runway width.(5) An example of this scheme may be found at Newark Airport.(15)

Method C

Method C (Fig. 26c) is generally used where overrun or cleared areas are specified at runway ends. At the threshold 40-foot bars extend outwards from the line of runway lights, satisfying the requirements for cleared areas.(5)

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*In the absence of any generally accepted nomen clature, the designations for the threshold lighting methods used in this paper are solely those of the authors.

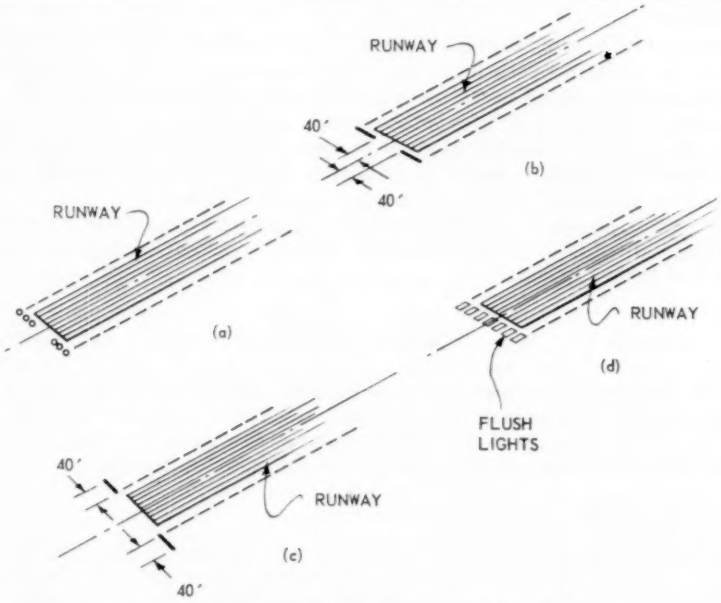

FIGURE 26-METHODS OF RUNWAY THRESHOLD LIGHTING.

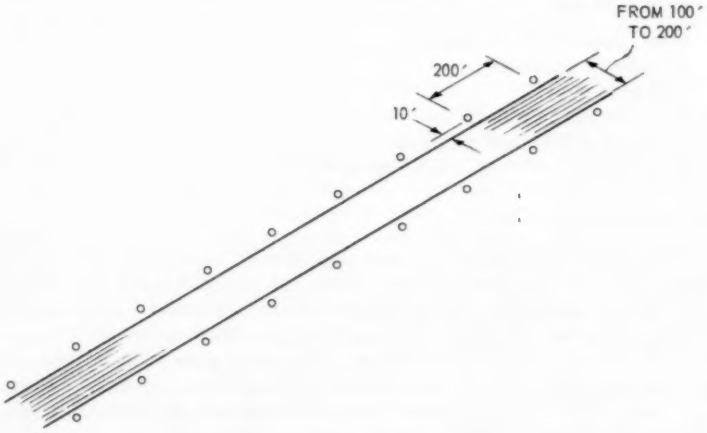

FIGURE 27-RUNWAY EDGE LIGHTING.

Scheme C is in operation, for example, at Pittsburgh Airport.(47)

Method D

Method D (Fig. 26d) utilizes flush mounted lighting units placed completely across the end of the runway for threshold identification.(53) This scheme may be used in cleared areas without presenting any hazard to aircraft. It is currently in operation at Schiphol Airport in Amsterday, and has been chosen by the Royal Danish Air Force for airports under its jurisdiction.(39) It has been recommended as a result of the March Air Force Base tests(57) and will probably be installed soon on a trial basis in the United States.

Methods B, C, and D all satisfy the design criteria of positive identification and design simplicity. In addition, they provide additional roll guidance to the pilots just before landing.

Runway Lighting

After completing his approach, a pilot must pull out of his approach path and fly almost parallel to the runway until he lands. No matter what the weather, in this final flare and landing phase of the transition from air to ground he is forced to rely entirely upon visual aids for guidance.

Design Criteria for Runway Lighting

The correct design of any runway visual aid demands an understanding of the basic guidance elements necessary during both good and poor visibility conditions. In good daytime visibility the paved runway and surrounding ground provide the necessary guidance. At night and in poor visibility lights are needed. The design elements which must be provided are the same as in the approach phase:

1. Identification of the runway
2. Alignment guidance
3. Roll guidance
4. Displacement guidance
5. Height and distance guidance
6. Simplicity of interpretation and guidance

Runway Lighting Systems

"At first night landings were made possible by floodlighting a general area. Boundary lights were added to keep planes out of ditches, fences, et cetera near the edge of airfields. When 'preferred landing paths,' or runways, were added to the original 'all-way' fields directional runway floodlighting was used in lieu of broad-coverage floodlighting. Next, someone added lights along the runway edges to help aircraft stay on the hard surface and not get bogged down in mud. The boundary lights were still retained in case small planes wanted to land on turf to line up better against the wind.

"Finally, the runway lights were made stronger and the floodlights and boundary lights were gradually abandoned. With a slight ground haze or ground fog there was a tendency for pilots to land on top of the powerful horizontal beams of runway floodlights. It was decided that it would be wiser and more economical to let pilots use their own airplane floodlights when atmospheric conditions were such that they could be used to advantage to augment

the runway lights. Boundary lights were discontinued because most night landings became confined to hard surfaced runways. Runway edge lighting systems were not used to any great extent until 1940 onward."(28)

Edge-Lighting Systems

The edge-lighting system shown in Fig. 27 is practically universally used. The light units are spaced on 200-foot centers along both sides of the entire runway. Lateral spacing between the two lines is dependent upon the runway width, usually varying between 100 and 200 feet. The standard color is white except on instrument runways, where aviation yellow lights are used for the first 2000 feet to aid the pilot in judging distances and to provide distinctive identification for instrument runways. The lights serve as beacons and are not intended to illuminate the runway pavement.

The "Black Hole" Effect

The edge-lighting system causes a "black hole" effect. As a pilot approaches the runway, the two rows appear to move upward and further apart. When flying between the rows and close to the ground, the edge lights can no longer be seen. Alignment, roll, height and distance guidance become ineffective, and the pilot is effectively flying blind. (A simple demonstration of this effect can be made by extending both hands a foot apart in front of you. If the hands are then slowly retracted, keeping them near eye level, the distance between hands will appear to increase.) "This condition is becoming increasingly dangerous as the 'jet age' approaches as these new aircraft not only land at higher speeds but are less stable just before touchdown."(55)

The black-hole effect led many pilots and engineers to suggest that more and brighter lights were needed along the sides of runways. Higher intensity lights and more lights in each row, as at Newark, were tried but found to be ineffective. Finally, Captail Gill of Eastern Air Lines suggested that the black-hole effect was due entirely to limitations of the eye.(27) This was later confirmed by several research organizations.(37)

The Eye in Relation to Runway Lighting Systems

The eye has sharp clear vision from only a small central area known as the fovea. Foveal vision represents less than five per cent of the total field of vision; the remaining portion (parafoveal vision) is sensitive only to color, change, and motion and deteriorates rapidly to almost nothing at the extreme edge of vision. In seeing the eyes focus on one point at a time and scan from point to point to take in an entire picture (saccadic movement).

A pilot scans with his eyes while over the approach zone. However, as the runway threshold nears, attention is concentrated straight ahead. The eyes are held motionless and when there is a lack of visual guidance in the foveal region focus on infinity. In this stare condition, information received from parafoveal vision is of minor importance.

The area of foveal vision has a spread of 2.5° to 3°, varying with the individual. Thus, if the angular vision required to encompass both rows of an edge-lighting system is greater than the foveal-vision angle, only a black hole will exist for the pilot. Table 1 gives the vision angle necessary to take in both sides of an edge-lighting system at different visual ranges. Perspective convergence of the runway lights causes the required visual angle to decrease as the visual range increases. With good visual conditions, it becomes possible to see those lights which fall into the foveal; however, they are too distant (more than 2500 feet) to provide proper guidance. In low visibility or

minimum RVR conditions, the required visual angle exceeds the foveal angle, and no lights can be seen for guidance.(10,27,37,40,47,55)

Table 1(37)

Required angular vision to encompass both sides of a runway at different visual range.
Perspective effects cause the vision angle to vary with the visual range.

Visual Range	Required Visual Range 200-foot runway	150-foot runway
2500 ft.	4.6°	3.4°
2000 ft.	5.8°	4.3°
1500 ft.	7.6°	5.7°
1000 ft.	11.3°	8.5°

Narrow-Gage Lighting

If a lighting system can be placed within the area of foveal vision, the black-hole effect should no longer exist. The first attempt to illuminate the middle of the runway was at Schiphol Airport, Amsterdam, Netherlands, an important facility plagued with low visibility conditions. A row of lights was embedded in the pavement on either side of the runway centerline, using the Elfaka flush-grid housing first developed there.(53) There are other installations in use at various North Atlantic Treaty Organization bases in Europe.(23)

An actual test of a temporary narrow-gage lighting installation was conducted by the CAA at Andrews Air Force Base near Washington, D. C. early in 1957.(24,48) During the night of April 26th, 25 successful approaches and simulated landings were made under extremely low visibility conditions. Temporary lighting fixtures were placed on the runway surface at various spacings and so arranged that nearly any combination of lights was available by simple electrical switching. The results appear to show that a 100 foot spacing at a 60 foot gage (30 feet each side of center-line) extending for 3000 feet at major airports would probably be best, with 2000 feet sufficient for smaller fields used by smaller aircraft. Test results with a similar system in the Royal Aircraft Establishment Cyclorama* have also been very favorable. The International Air Transport Association (IATA) has recommended the installation of narrow gage runway lighting for minimum RVR operation.(10)

Mr. Arthur E. Jenks (Chief, Flight Inspection Division, CAA) has proposed such a system with two closely spaced rows of triple flush units transversely paired each 100 feet to provide roll guidance.(37) If the configuration were standardized accurate height guidance would be available as well, with apparently increasing separation of the two rows of linear bars and closing of the distance between them at a familiar rate as the pilot descends, permitting precise height judgments.(37)

*The Cyclorama is a device which simulates a pilot's view of approach and runway systems. It presents a perspective picture which changes just as the pilot's view and actual visual aid does.

Discussion continues as to whether centerline guidance lights should be installed between and beyond the narrow gage lights, what their longitudinal spacings should be, whether they should continue the entire length of a runway as an aid to planes taking off, how many feet of narrow gage lighting is really needed and what gage should be used; the answers to these problems will probably have to await further experience with actual installations. All agree that edge lighting would still be needed to define the sides of the runway, especially beyond the termination of the narrow-gage installation. Development work continues on alternate designs of these lighting fixtures.

Narrow gage lighting is now being installed in the first 3000 feet of new runways at Dow Air Force Base[20] and at New York International Airport.[62]

Floodlighting

The historical background of runway floodlighting has already been described.

At the Andrews tests a new system of edge floodlighting for runways was tested and found promising[48] though still needing further development.[48] Its purpose is to illuminate the "black hole" so that better height guidance will be available than can be obtained from either the last bars of the Configuration "A" approach lighting system or the conventional runway edge lighting.

The "Fluorescent Runway Strip Lighting" makes use of the newly developed very high output (VHO) fluorescent lamps housed in a specially designed low luminaire which casts the light across the runway surface at a grazing angle that vividly brings out pavement texture, gives little glare and produces a completely different effect than lighting from higher elevations. Suggested installation is on both sides at nine foot centers starting 200 feet from the threshold and continuing for approximately 1400 feet. Further testing is in prospect early in 1958 on 1300 feet of the instrument runway at Washington National Airport.[25]

Taxiway Lighting

Design Criteria

Taxiways are the vital arteries between the runway and parking apron. Their visual aids must meet the following criteria for night and low visibility guidance:

1. Distinctive clues to prevent confusion of taxiways and runways
2. Rapid identification of specific taxiways
3. Guidance along the taxiway
4. Guidance at taxiway and taxiway-runway intersections
5. Effective, simple presentation of guidance elements to permit rapid aircraft movement between runway and apron

Taxiway Lighting Methods

The taxiway lighting schemes described are often used separately, but can be effectively combined to provide swifter guidance. In addition, signing techniques may be added to any lighting method.

Side Lighting

The side-lighting system consists of a row of lights on each side of a taxiway at longitudinal spacings not to exceed 200 feet. On curves and at intersections spacing is decreased to facilitate identification and guidance.

ICAO standards state that "when lights are placed along the sides of the taxiway, they shall be either blue on both sides or blue on one side and yellow on the other."[31] While older filament lamps with blue glass filter ". . . are inherently inefficient, screening out and wasting much of the total generated light"[26] the newer gaseous tube lights generate blue light fairly efficiently.[28] This may make the provision for two colors of lights no longer necessary.

The United States has adopted the side-lighting scheme for its national standard; centerline schemes are so far not permitted.[6]

Centerline Lighting

A centerline lighting scheme may be used for taxiways; its proponents argue that they will give better guidance, especially at the new high speed taxiway turnoffs.[48] As now installed in Europe, lights are spaced at not to exceed 200 feet and decreased at curves and intersections. At intersections additional lights are required at both taxiway sides for further identification and guidance. Centerline units must not present a hazard to aircraft, limiting design to the more costly and difficult to maintain flush or semiflush fixtures. By international agreement, centerline systems emit a green colored light to prevent confusion with side-lighting systems. However, since this green could be confused with threshold lighting the units must be shielded to prevent their being seen from the air.[31]

Centerline taxiway lights were installed at the new Central Airport, London, England;[4] other centerline installations have been made since in France and the Netherlands.

Experimental Centerline Installation at Indianapolis

An experimental centerline lighting system for a high speed taxiway turnoff should be completed at Indianapolis airport by January 1958; the opportunity was seized of installing it in a runway that was still under construction. Blue flush uni-directional lights of a new design will be located along 800 feet of taxiway centerline leading from a strip of 1200 feet of white flush runway centerline lights; 12 lights spaced at 100 feet apart. A blue flashing flush light will be provided on this runway centerline 500 feet before the point of tangency of the turnoff.[25]

Taxiway Signs

The complexity of modern airports has necessitated the development of additional taxiway guidance in the form of signs.

> "Rolling down the flat surface of a runway, a pilot often sees a lighted taxiway as a confused jumble of blue lights off to the side. Perspective plays tricks on him. But there's no mistaking a sign with a brightly lighted arrow and legend."[58]

Taxiway sign systems supplement instructions of a ground traffic controller and aid the pilot in complying with them. They consist of two basic types, destination signs to indicate the direction to a particular area of the airport and intersection signs to identify intersecting routes. Signs have been standardized by CAA with respect to size, shape, lettering, color and location. At New York International Airport signs with translucent yellow letters and symbols mounted on a black box with a light inside are very effective in fog or at night.[13]

Authors' Comments

In this paper the authors have discussed the physical and psychological problems involved in the approach and landing of an airplane on an airport runway. From them they have developed a set of design criteria by which they have reviewed and evaluated the various systems of airport approach, threshold, runway and taxiway lighting. Some of these systems are now historical, some are in current use and others are still undergoing development. Together they form a record of active design progress and change during the less than twenty years that lighting equipment designed for low visibility and landing has been in use. Throughout there runs the thread of empirical development and testing and gradually increasing understanding of what will best serve the needs of landing aircraft.

The authors urge that a "systems" approach be used in the design of airport lighting. The transition of an airplane from air to ground should be an integrated process. A landing begins when the pilot commences his final approach. The landing process should be considered complete only when the plane finally rolls to a stop before the apron loading gates.

It has been customary to design separately the visual aids provided in the approach, runway and taxiway areas without regard to the interdependence of them. In the United States, lighting bulletins issued by the Civil Aeronautics Administration deal separately with the three related areas. Even an economic differentiation exists in this country where, roughly speaking, the Federal Government will pay 100% for approach lights, 75% for high intensity runway lights on designated instrument runways and 50% for other airport lighting.(18,28)

It is heartening to note that a complete and integrated airport lighting "system" appears to be emerging. In the United States this will probably comprise the following:

(a) Approach lighting—Configuration "A" supplemented by flashing condenser discharge lamps, with the final 1000 feet adjacent to the runway on military airports being housed in flush recessed fixtures.

(b) Threshold lights—a row of flush recessed fixtures across the runway end, showing aviation green, possibly supplemented by additional raised wing bars extending outward from the line of runway lights.

(c) Runway lights—a continued use of conventional runway lighting as now used, supplemented by flush narrow gage lighting on the first 3000 feet of the runway, with similar lights marking the centerline for a longer distance. Edge floodlighting of runways might supplement the other lighting equipment.

(d) Taxiway lights—some form of flush lighting starting at the runway centerline and continuing into the taxiway so as to guide aircraft off the runway quickly and easily, followed by conventional taxiway edge lighting possibly supplemented by some flush lights and by directional signs to and from the apron.

The lighting system outlined above forms a very expensive package—one which can be foreseen only on a few of the largest civil and military airports. Some components, such as narrow gage lighting, do not lend themselves to installation in already existing runways without excessively costly construction and placing a runway out of service for some time; they may be installed in new runways or runway extensions. At already existing large airports some features like the Configuration "A" approach lighting system are coming into

wider use, and flush mounted threshold lights and runway edge floodlighting may find favor as well. At smaller airports development beyond already installed lighting systems will be forced by economic considerations to be slow.

It does not appear that any world-wide single standard of airport lighting is going to develop, the cost of conversion of existing systems being prohibitive. The liberal approach-lighting policy of the International Civil Aviation Organization (ICAO) appears more realistic; this specifies only that approach systems must include a row of lights along the extended runway centerline with one or more transverse rows.(31) This definition would permit the Calvert System, Configuration "A" and "B" and other schemes as well. The authors feel that any system which satisfies the necessary design criteria will provide at least adequate landing guidance. Conversion to a single standard would, if nothing else, stifle the natural development of better approach systems.

Outmoded systems should, of course, be scrapped in the interests of greater flying safety; this will reduce in number the eleven major approach configurations plus variations that were still in existence in the United States early in 1957.

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The authors have submitted this paper to several authorities, including the staff of the Civil Aeronautics Administration, for review and have received many helpful suggestions from them, most of which they have attempted to incorporate into the final draft. The authors take full responsibility for all facts, ideas and opinions expressed in this paper. The reader must bear in mind at all times that there are many aspects of airport lighting which have been and still are highly controversial; the authors have attempted to present this material as objectively as possible and can only hope they have succeeded in doing so. They will, of course, heartily welcome any discussion which may follow.

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MUNICIPAL FINANCING OF AIRPORTS[a]

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Municipal Financing of Airports

In the first half of the eventful century in which we are now living we witnessed the expansion of transportation industries to heights never dreamed of by those who invented the steamboat, the steam locomotive, the automobile and the airplane. We saw facilities and equipment developed for the movement of vast quantities of raw and manufactured products through our rivers, lakes and oceans. We saw the development of a network of railroads for the transportation of persons and commodities to most every point in this land. The motor car has perhaps been one of the greatest influences in our economy and mode of living. Every city is wrestling with the problem of the movement and control of traffic volumes two or three times in excess of the capacity of existing facilities. No one seems to know when the peak will be reached. We do know that huge sums are being expended at all levels of government for arteries for more rapid and safe movement of the millions of passenger cars, trucks, and buses.

The latest and most modern means of transportation is by airplane. While this mode of transportation has experienced phenomenal growth there are those who content that it is yet in its infancy. As we recall the accomplishments of the past it is difficult to dispute this contention. It was only thirty years ago that, to the bewilderment of the world, Charles Lindberg made the first solo trans-Atlantic flight from New York to Paris. This flight required thirty-three hours and thirty-two minutes. Today there are many flights each day over this route and to all major cities of the world. The flying time now from New York to Paris is eleven hours. Each year this time decreases. There is little question that the Lindberg flight played an important role in removing doubts as to possibilities in aviation. It was not long after this that Lindberg was assisting in the establishment of airmail

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transportation and charting of possible routes for airlines in this country. While it might have appeared that the development of airline transportation was retarded by World War II the advances of aircraft for military uses and the utilization of airlines for essential transportation paved the way for the phenomenal growth that we have witnessed since that world conflict.

An Associated Press story released from Washington January 30 this year reported an announcement by the Civil Aeronautics Board that the airlines have surpassed both railroads and bus lines in passenger-miles of traffic. According to the Board, scheduled and nonscheduled airline passenger-miles totaled 25,800,000 in 1957. This slightly exceeded the amount reported for bus lines and was approximately four million more than the reported amount for intercity railroad passengers. The Civil Aeronautics Board predicted that passenger air traffic would continue to increase.

Municipal government has played an important role in the development of the aviation industry. Like many other activities which local government has had to assume, the development and operation of airports came somewhat by default. Private interests seemed unwilling to invest capital for such a venture. The state governments had no concern in this problem then and have little, if any, at present. While the Federal government now has a definite interest in the development of our airports and is contributing substantial sums for such a program, the initial steps were usually taken by local government. Public attitude remains unchanged and thus far there has been little indication that private capital will enter the field of airport development and operation - that is, on the scale that seems necessary.

Thus we find our municipalities in a business venture which has required capital outlays running into many millions of dollars. In a survey conducted in 1946 by Professor Lynn L. Bollinger of the Harvard School of Business, it was predicted that the investment in terminal-type airports would soon surpass the two billion dollar level. There seems to be no data published which reveals the present investment in airports, but from information I have gathered, there is little doubt but that the amount is substantial and approaches the prediction of Professor Bollinger. Cash expenditures through Federal grants for the fiscal years 1946 to 1957 inclusive totaled $227,820,587. The bonded debt for airport purposes of those cities responding to an inquiry has increased from one to ten times since 1946-47.

Except for the airports serving New York City which are operated by the Port Authority of New York, a substantial amount of the financing has been through general obligation bonds. This method of financing is comparatively simple. In most states this type of bond requires approval at an election. The necessary majority in many states is two-thirds of those voting on the proposition. In most states, the limitation as to the amount of such bonds that may be authorized or issued is based on a percentage of the assessed valuation. Some cities vote the bonds on the basis of current needs whereas others may vote issues for a program of improvements which may extend over a period of several years. While revenues of the airport, if not otherwise pledged, may be used to service and retire general obligation bonds, such bonds are not dependent on these revenues but usually bear the full faith and credit of the taxing power of the issuing agency. Because of this, the general obligation bond is usually more attractive as an investment and thus carries a lower rate of interest.

It might be pointed out here, that according to a survey which was made for the preparation of this paper it was found that general obligation bonds

are serviced from tax revenues in nine of thirteen cities having such debt for airport purposes. In other words, 30% of these cities were servicing all of the airport general obligation debt requirement from airport income. More than 20% of Kansas City's tax rate for debt service for 1958 will be used to service general obligation bonds now outstanding or which are planned for early issuance for airport purposes. It should be noted, however, that beginning with the next fiscal year Kansas City should be able to utilize $150,000 to $200,000 from current income for capital improvements. This amount should increase in subsequent years.

Increasing demands for public improvements to meet expanding areas, population growths, and catching up with deferred needs which accumulated during the depression and war years have utilized much of the borrowing margin. Rising cost of improvements has also been a major factor in the diminution of the borrowing capacity. Had the pattern of assessed valuations followed economic trends, this situation would have not become so critical in some cities. Some states have taken cognizance of this situation and permitted increases of the debt margin.

Faced with this situation, together with the view that there is a limit beyond which a city should not obligate itself with tax supported bonds for aviation facilities, some cities have turned to the use of revenue bonds for financing some of these needs. While this type of bond is not new, until recently, its use had been limited primarily for financing public utility improvements. It is believed the first revenue issue for airport purposes was a $1,750,000 Denver issue dated September 1, 1951. Since that time, revenue issues have been sold by Dade County, Atlanta, Phoenix, Dallas, San Antonio, and Kansas City. The Port of New York Authority uses revenue bonds exclusively for financing improvements but such bonds also have the support of revenue from other facilities operated by the Authority.

Under the best of circumstances, airport revenue bonds have not been considered an attractive security for investment unless, of course, they carry high yields. This resistance is mainly due to the lack of experience in this method of financing and the relative newness of aviation development and operation.

The $18,700,000 issue marketed by Kansas City in 1954 can hardly be considered a typical airport revenue issue. This issue is supported primarily from rental income paid by Trans World Airlines for the overhaul base facilities which were provided from the proceeds of the issue. For this reason, it contained certain bond covenants not usually found in other airport revenue issues. For example, net revenues from airport operations cannot be used for debt service of general obligation bonds. After a secondary reserve has been established to support the revenue bonds, such net revenues may then be used for airport development. While this provision was resisted, the investment bankers contended it was necessary to make the bonds saleable. Instead of being detrimental, this provision may be a blessing in disguise, since it will permit some of the airport development program to be undertaken on a pay-as-you-go basis. It is conceivable that within ten years most or all of the airport developments can be financed from current income.

In marketing this issue as well as several other major revenue issues, we have been exposed to the basic principles underlying revenue financing.

Since the payment of interest and principal on revenue bonds is usually dependent on net revenues of the facilities which are being developed, the

bond indenture must contain certain protective provisions to assure the investor that these obligations will be paid when due. Those who prepare the issue for marketing must rely on certain information which is developed by engineers.

In the first place, the investor will want some assurance that the amount of bonds being offered will complete the project which is being financed by such bond issue. The investor wants to be sure that his investment will not be diluted by having additional bonds which would be supported from the revenues of the facility. If sound estimates cannot be furnished it may be necessary to obtain bids. Investment bankers and the ultimate purchasers will not accept estimates of the city engineer, but require that this data be provided by a recognized firm of architects or engineers having experience in the particular field. It might be pointed out that similar requirements are made relative to the legal aspects of a bond issue. There are relatively few law firms whose legal opinions on bond issues are acceptable. There may be instances where findings and the opinion of more than one firm of engineers or architects will be necessary to satisfy the investor and attract a more favorable market for the bonds.

Because the facility being developed from proceeds of revenue bonds will not usually be capable of producing revenue for servicing the debt until it is completed, it is common practice to capitalize the interest cost for the period of construction. In keeping the amount of the bond issue at a minimum, the mistake is sometimes made of not including enough interest periods in the financing. Such action is often taken, however, on the basis of estimates of completion dates provided by the engineers. The bond covenants are usually such as to prevent the raiding of excess moneys reserved for interest should the project be completed in advance of the scheduled date. In short - the construction schedule and date of final completion must be realistic. Otherwise, a default of interest payment may occur. It is fully realized that some construction delays may be avoided or minimized if penalty provisions usually found in the construction contracts are rigidly enforced. Penalty provisions that cannot be enforced should not be in the specifications and contract.

As has been pointed out, - the principal and interest of revenue bonds are paid from the revenues of the facility or facilities being developed. Before a ready market may be found for these bonds, data must be supplied which will present to the investor the proposed operating results and the plan of bond and interest retirement. The preparation of such a report for a "going concern" such as a water or light utility is not too difficult. A pattern of experience is available from financial, operating, and other data. Then too, water and electricity are necessities to the daily life of each of us. Such is not necessarily the case for a hangar, a terminal building or any other portion of an airport.

While certain patterns of experience may be available from past operations of an airport, the investor will require independent analysis from engineers, public accountants and others qualified to project the future and determine the feasibility of the improvements to be developed from the proposed bond program. If the issue is for general airport development, the investor will want to know the probable dates and amounts that will be needed to make additional improvements - and how such will be financed. He will desire information as to the determination of rates for various charges, how they compare with other airports, and whether they are ample to meet operating, maintenance, and debt charges.

It is well to discuss at this point the matter of bond coverage. The margin of coverage is one of the major factors in marketing a revenue issue. The greater the coverage - the lower the rate of interest on the bonds. Coverage is normally considered as the margin of net revenue remaining in any one year after the payment of principal and interest requirements. For example, if projected net revenues for a particular year are $150,000 and debt service is $100,000 the coverage factor is 150. Thus, there is a safety margin of $50,000 expected for that year. An airport issue should have a coverage of 175 to 200 whereas a water or light utility issue can usually find a favorable market with a coverage of 125 to 150.

In considering additional revenue issues, the principal and interest requirement of such issues must also be included. Usually the new or increased revenues from the expanded facilities made possible by such additional bonds is ample to provide the required coverage. Otherwise, the rate structures of the existing facilities must be adjusted to accomplish the results required.

The investor will also require data on the credit stability and operating experience of the principal tenants of those facilities which are to produce the revenue for servicing the bonds.

The indenture for most revenue issues in addition to the requirement of annual audits and reports by independent certified public accountants also call for periodic appraisal of operations and the physical condition of the facilities during the life of the bond issue.

These are the more important requirements that may be expected if financing is done by revenue bonds. There are those who say that a city is dominated by the bondholders when it obligates itself thusly. If these requirements are good for the investor they should be even more valuable to the municipality. Most of such requirements merely represent sound business practices.

What may we expect in the future? We can be reasonably sure that the trend of the past decade will continue. With the introduction of jet aircraft, demands are being made for lengthened runways. Heavier aircraft will require runways of greater strength. Increased air traffic will require additional airport facilities such as runways, terminal accommodations, hangars, and other improvements. Probably additional airports will be necessary. It is quite possible that, as the skyways become crowded with aircraft, expensive equipment will be required for its safe movement and protection to the public. Whether private capital will provide facilities for the accommodation of helicopter service is not known. It is reasonable to expect that air express and freight movements will continue to increase.

These contentions are supported by a statement recently made by Milton W. Arnold, Vice President, Operations and Engineering of Air Transport Association. To quote from Mr. Arnold's statement -

> "Civil aviation is growing by leaps and bounds — private corporate, and business flying, as well as the commercial airlines. From March, 1956 to March, 1957, at the 12 largest cities in the U. S., civil aviation increased by almost 19 percent. Airline operations increased almost an equal amount — over 18 percent. This is the increase demanded by the flying and travelling public. Even if this rate of increase is cut in half, then most cities must provide for 100 percent increase in capacity by 1967 at their already-crowded airports. Some cities will require an even greater capacity."

Not only will substantial sums be needed for the development of additional airport facilities but large amounts must be provided for the expressways and other facilities for transporting passengers and air cargo from the airport to the central city. While the helicopter may become one of the chief means of transporting passengers into and from the city and between airports with a metropolitan area, there will still be heavy volumes of surface transportation.

With the experience gained during recent years, together with the fact that the aviation industry is now in more capable hands, the future course of airport development can be more carefully and wisely charted.

The program for the future deserves the cooperative effort of manufacturers of aircraft, airlines, local and federal authorities with the assistance of organizations such as yours. Attention must also be given to the financial aspects of such a program. With a properly coordinated program many costly mistakes can be avoided. Your organization can render a real service to your government by cooperating with the aviation industry in planning the future needs for accommodation of this rapidly growing business.

While a few cities will use some revenue bonds, most cities indicate preference to general obligation bonds. There is indication that more money will be provided from current income than has been provided in the past. Under Public Law 211 there is assurance of Federal aid in the amount of $63 million for each of the fiscal years 1958 and 1959.

I am one who believes that airlines and other users of airports must assume a greater portion of the cost of providing and operating airport facilities. We must, however, not fail to realize the revenue potentials that may be generated by airline traffic. Substantial sums are being collected at many airports from parking, restaurant, and many other concessions. In light of the substantial investment in airport facilities there is little justification for free parking and permitting other uses of airport properties without adequate compensation for their use.

Like many cities Kansas City is pressing forward in preparation for the jet age. The runway on its new International MidContinent Airport is now being extended from six to nine thousand feet. Other field improvements on this 4600 acre airport are in the final planning stages and their construction will probably be started in 1959. Development of the first unit of the terminal facility at the new airport should follow with construction scheduled to commence probably in 1960. The program of development of this airport not only contemplates the accommodation of jet and other heavy aircraft, but is aimed to provide areas and facilities for major installations of other airlines and for the location of industries allied to the field of aviation.

With the relocation of facilities for fixed based operators, areas have been released for an expansion program, now underway, of terminal and other needed facilities at our Municipal Airport. While area limitations will not permit the extension of the 7,000 foot runway on this airport, because of its convenient location (five minutes from the heart of downtown Kansas City) the airlines and others have recommended continued operations from this airport.

One of the major airlines of the world, Trans World Airlines, Inc. originated in and still maintains Kansas City as its headquarters. Because of this Kansas City is keenly conscious of the importance of aviation to its economy.

I have every reason to believe that Kansas City and all other cities with major airport installations will continue to meet the challenges of this modern age. Aviation has been a means of shortening the distance between the countries of the world. Let us also hope that it will be a means to a better understanding between mankind and the nations of the world to the end that we might share together the ideals and precepts of him who came as the Prince of Peace.

PROCEEDINGS PAPERS

The technical papers published in the past year are identified by number below. Technical-division sponsorship is indicated by an abbreviation at the end of each Paper Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Pipeline (PL), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways and Harbors (WW), divisions. Papers sponsored by the Board of Direction are identified by the symbols (BD). For titles and order coupons, refer to the appropriate issue of "Civil Engineering." Beginning with Volume 82 (January 1956) papers were published in Journals of the various Technical Divisions. To locate papers in the Journals, the symbols after the paper numbers are followed by a numeral designating the issue of a particular Journal in which the paper appeared. For example, Paper 1449 is identified as 1449 (HY 6) which indicates that the paper is contained in the sixth issue of the Journal of the Hydraulics Division during 1957.

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JULY: 1289(SM3), 1290(EM3), 1291(EM3), 1292(EM3), 1293(EM3), 1294(HW3), 1295(HW3), 1296(HW3), 1297 (HW3), 1298(HW3), 1299(SM3), 1300(SM3), 1301(SM3), 1302(ST4), 1303(ST4), 1304(ST4), 1305(SU1), 1306 (SU1), 1307(SU1), 1308(ST4), 1309(SM3), 1310(SU1)[c], 1311(EM3)[c], 1312(ST4), 1313(ST4), 1314(ST4), 1315 (ST4), 1316(ST4), 1317(ST4), 1318(ST4), 1319(SM3)[c], 1320(ST4), 1321(ST4), 1322(EM3), 1323(AT1), 1324 (AT1), 1325(AT1), 1326(AT1), 1327(AT1), 1328(AT1)[c], 1329(ST4)[c].

AUGUST: 1330(HY4), 1331(HY4), 1332(HY4), 1333(SA4), 1334(SA4), 1335(SA4), 1336(SA4), 1337(SA4), 1338 (SA4), 1339(CO1), 1340(CO1), 1341(CO1), 1342(CO1), 1343(CO1), 1344(PO4), 1345(HY4), 1346(PO4)[c], 1347 (BD1), 1348(HY4)[c], 1349(SA4)[c] 1350(PO4), 1351(PO4).

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NOVEMBER: 1426(SM4), 1427(SM4), 1428(SM4), 1429(SM4), 1430(SM4)[c]. 1431(ST6), 1432(ST6). 1433(ST6), 1434(ST6), 1435(ST6), 1436(ST6), 1437(ST6), 1438(SM4), 1439(SM4), 1440(ST6), 1441(ST6), 1442(ST6)[c], 1443(SU2), 1444(SU2), 1445(SU2), 1446(SU2), 1447(SU2), 1448(SU2)[c].

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FEBRUARY: 1528(HY1), 1529(PO1), 1530(HY1), 1531(HY1), 1532(HY1), 1533(SA1), 1534(SA1), 1535(SM1), 1536(SM1), 1537(SM1), 1538(PO1)[c], 1539(SA1), 1540(SA1), 1541(SA1), 1542(SA1), 1543(SA1), 1544(SM1), 1545(SM1), 1546(SM1), 1547(SM1), 1548(SM1), 1549(SM1), 1550(SM1), 1551(SM1), 1552(SM1), 1553(PO1), 1554(PO1), 1555(PO1), 1556(PO1), 1557(SA1)[c], 1558(HY1)[c], 1559(SM1)[c].

MARCH: 1560(ST2), 1561(ST2), 1562(ST2), 1563(ST2), 1564(ST2), 1565(ST2), 1566(ST2), 1567(ST2), 1568 (WW2), 1569(WW2), 1570(WW2), 1571(WW2), 1572(WW2), 1573(WW2), 1574(PL1), 1575(PL1), 1576(ST2)[c], 1577(PL1), 1578(PL1)[c], 1579(WW2)[c].

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MAY: 1621(HW2), 1622(HW2), 1623(HW2), 1624(HW2), 1625(HW2), 1626(HW2), 1627(HW2), 1628(HW2), 1629 (ST3), 1630(ST3), 1631(ST3), 1632(ST3), 1633(ST2), 1634(ST3), 1635(ST3), 1636(ST3). 1637(ST3), 1638(ST3), 1639(WW3). 1640(WW3), 1641(WW3), 1642(WW3), 1643(WW3), 1644(WW3), 1645(SM2), 1646(SM2), 1647 (SM2), 1648(SM2), 1649(SM2), 1650(SM2), 1651(HW2), 1652(HW2)[c], 1653(WW3)[c], 1654(SM2), 1655(SM2). 1656(ST3)[c], 1657(SM2)[c].

JUNE: 1658(AT1), 1659(AT1), 1660(HY3), 1661(HY3), 1662(HY3), 1663(HY3), 1664(HY3), 1665(SA3), 1666 (PL2), 1667(PL2), 1668(PL2), 1669(AT1), 1670(PO3), 1671(PO3), 1672(PO3), 1673(PL2), 1674(PL2), 1675 (PO3), 1676(PO3), 1677(SA3), 1678(SA3), 1679(SA3), 1680(SA3), 1681(SA3), 1682(SA3), 1683(PO3), 1684 (HY3), 1685(SA3), 1686(SA3), 1687(PO3), 1688(SA3)[c], 1689(PO3)[c], 1690(HY3)[c], 1691(PL2)[c].

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c. Discussion of several papers, grouped by divisions.

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